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# VEGETATION MANAGEMENT FOR WATER YIELD IMPROVEMENT IN THE COLORADO RIVER BASIN

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# Vegetation Management for Water Yield Improvement in the Colorado River Basin

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In cooperation with
Water and Vegetation Management and Executive Subcommittees
of the
Pacific Southwest Interagency Committee

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Abstract

Water yield from forest and rangelands can be augmented by managing vegetation and snow to reduce evapotranspiration. Methods of managing vegetation include clearing, type conversion, patch cutting, and thinning. Snow can be trapped in forest openings and by snow fences in windswept treeless areas to reduce evaporation of windblown snow and concentrate snowmelt to enhance its delivery to streams. Some arbitrary augmentation goals were chosen to illustrate the potential for increasing water yield, and treatments were hypothesized to get these increases. Most of the water produced by vegetation management would be cheaper than imported water, and some of it from commercial forests would be in the price range of water produced by weather modification.

Keywords: Watershed management, snow management, land use, forest land, brushlands, surface waters, runoff, watersheds

## Foreword

This report was prepared under the auspices of the Pacific Southwest Interagency Committee (PSIAC). It completes the first phase of a four-phase proposal, prepared by an ad hoc subcommittee appointed by the Chairman of PSIAC, to achieve increased water yields by vegetation management.

The Ad Hoc Subcommittee requested USDA Forest Service participation in this study because the Forest Service did much of the research in this field and because the potential for increasing water yield by vegetation management is greatest in the National Forests and other public lands.

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# Vegetation Management for Water Yield Improvement in the Colorado River Basin

Alden R. Hibbert

## Management Implications

Water yield response to management of vegetation and snow was determined for 11 vegetation types within the Colorado River Basin after a thorough review of research findings from the past 50 years. The greatest response can be expected on sites where transpiration or evaporation from snow can be greatly reduced. Clearcutting and type conversion usually cause the largest increases in streamflow in forests and brushlands Where there is much snow and wind, a network of small patch cuts effectively concentrates snow in forest openings, thereby increasing snowmelt contribution to streamflow. In windswept, treeless areas, particularly selected sites in alpine, high elevation sagebrush, and mountain grassland areas, evaporation of blowing snow can be reduced by trapping snow in large drifts behind snow fences, where it more effectively contributes to streamflow

Flow of the Colorado River could be increased as much as 4 million acre-feet in the Upper Basin and 2 million acre-feet in the Lower Basin if all forest and brush lands were managed solely to increase water yield. However, these are unrealistic goals when other forest resource, economic, social, and environmental concerns are considered.

Clearcutting and type conversion may be appropriate in several vegetation types, such as the chaparral and mountain brushlands, where commercial values are low and forage and wildlife habitat can be enhanced by creating brush-grass mosaics and greater plant diversity Where clearcuts and type conversions are not acceptable management practices, the potential for increasing water yield is less but still substantial in many cases.

Setting a realistic goal for increasing water yield through vegetation management requires a careful balance among needs, costs and resource capabilities. The water user wants to know the number of acre-feet of water that can be produced and the cost. The land manager, in contrast, must decide on resource allocations based on public involvement and legal requirements. Because of the many uncertainties, no attempt was made in this paper to specify the amount of additional water that could be produced by management of vegetation and snow, except to show how arbitrary amounts might be generated by applying hypothetical treatments to portions of the Basin. The examples chosen were not meant to suggest an attainable level of water yield increase, but rather to show the kinds of treatments and how much area might be affected, given an augmentation goal.

From the hypothetical examples used, it appears that 500,000 acre-feet of extra water (3.5% increase) could be generated in the Upper Basin without treating more than 22% of any vegetation type, except aspen, in which 40% would be treated. About one-half of the increased yield would come from the subalpine forests, including Douglas-fir. In the Lower Basin, treatments would need to be more extensive to generate 250,000 acre-feet, an 8% increase in water yield. Attention would focus on the chaparral and ponderosa pine forests, where 92% of the total increase would be generated. To get this amount of water would require treatment of about 20% of the chaparral and 33% of the ponderosa pine. In actual practice, economics would strongly influence the treatment priorities.

While information on cost of producing extra water is incomplete, it is believed that the least expensive water would come from commercial forests where timber yields would pay for part of the treatment costs. Water would be more expensive from type conversions because most of the treatment costs would be levied against water production. Most of the water would be cheaper than imported water, and some of the water from commercial forests would supplement and be in the price range of water produced by weather modification.

Water yield improvement projects would require several decades to become fully effective in commercial forests, where the rotation age of tree harvest may vary up to 120 years or more. Type conversion in brushlands could become operational much faster. Water yield response to treatment is well defined in the chaparral but less so in the mountain brush, where more information is needed to determine their suitability for treatment.

In summary, there is considerable potential for increasing water yield by vegetation management in the Colorado River Basin. However, the full potential is not attainable because other demands on the forest resource must also be considered. To materially improve water yield, greater emphasis would have to be placed on management strategies that favor water production. The hypothetical examples used in this study to illustrate the potential would increase basin water supply by nearly 5%.

## Introduction

The Colorado River is one of the most completely utilized rivers in the world. The combined surface and ground water supplies are generally adequate, but completion of the Central Arizona Project and development by the Upper Basin states of their water apportionments could result in water shortages as early as 1995.[2/] Local shortages already exist in portions of the Basin, and ground water is being used much faster than it is being replenished. Vegetation management is one method of augmenting water supplies by reducing evapotranspiration (Hibbert 1967, Anderson et al. 1976).

Several independent projections have been made since 1960 on the potential for increasing water yield by vegetation management in the western United States, including the Colorado River Basin. The earlier estimates are summarized and discussed in Appendix II. This paper reevaluates water yield improvement potential for 11 vegetation types within the Colorado River Basin. The detailed analyses were put in Appendix I to maintain continuity of the paper. These new estimates are based largely on updated results of vegetation treatments on small watersheds and related research. Finally, the estimates are summarized for the Upper and Lower Basins, and are discussed in terms of economic feasibility, environmental concerns, and other considerations.

## Major Objectives of the Study

1. Summarize and evaluate existing knowledge of vegetation management for water yield improvement in forest and range vegetation types within the Colorado River Basin. (The study includes upstream riparian vegetation along relatively small streams that drain to the Colorado River and its major tributaries. However, the study does not include downstream riparian vegetation along the major streams; Horton (1976) reported the management status of these areas.)
2. Assess the adequacy of the knowledge to determine water yield potential by vegetation management practices.
3. Consider the effects of treatments for water yield on other resources and the environment.
4. Determine costs and benefits of potential increases to the extent possible with existing information.

## Major Sources of Information Used in the Study

1. Watershed management status of knowledge papers by vegetation types in the Rocky Mountain and southwestern areas published by the Rocky Mountain Forest and Range Experiment Station provided much of the scientific base for this report.

2. Numerous scientific articles and technical papers were reviewed for information to strengthen this study. Two in particular summarize knowledge of water yield improvement activities. One by William Sopper[3/] in 1971 dealt with water supply augmentation by watershed management in wildland areas; the other by Anderson et al. (1976) summarizes what is known about the effects of forest management on floods, sedimentation, and water supply in the United States.

3. Comprehensive framework studies were conducted by the Upper and Lower Colorado Region State-Federal Interagency Groups for the Pacific Southwest Interagency Committee (PSIAC) to provide detailed river basin plans for the development, use, and management of water and related land resources. Two extensive reports were published separately:

   Upper Colorado Region Comprehensive Framework Study consisting of main report plus 18 appendices (PSIAC 1971a). Lower Colorado Region Comprehensive Framework Study consisting of main report plus 18 appendices (PSIAC 1971b).

4. The Pacific Southwest Hydrologic Analysis Phase I (USDA Forest Service 1967-1968)[4/] survey and analysis made a first approximation of the potential for improving water yield and for reducing sediment yield from National Forest System lands tributary to the area to be benefitted by the Pacific Southwest Water Plan, including Upper and Lower Basins of the Colorado River.

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[2/] U. S. Department of Interior, Bureau of Reclamation. Executive summary of critical water problems facing the eleven western states. Westwide Study. 85 p.

[3/] "Watershed Management--Water Supply Augmentation by Watershed Management in Wildland Areas" by William E. Sopper, National Water Commission Report NWC-EES-72-028. 149 p.

[4/] Unpublished reports prepared by USDA Forest Service Rocky Mountain Region, Lakewood, Colo.; Southwestern Region, Albuquerque, N. Mex.; and Intermountain Region, Ogden, Utah.

5. The potential for increasing water yield in Arizona by vegetation management was assessed by Ffolliott and Thorud (1974). University of Arizona Technical Bulletin 215 (1974) summarizes a much more detailed document[5/] that contains an excellent bibliography of watershed and related material.

## Water Resources of the Colorado River Basin

The Colorado River drains about 250,000 square miles (160 million acres) in the southwestern United States (fig. 1). The Basin includes virtually all of Arizona and portions of New Mexico, Colorado, Wyoming, Utah, Nevada, and California. The small portion in California is desert along the lower main stem of the river, and is of little consequence to this study, since it produces very little water and has no potential for increasing the supply other than by control of phreatophytes.

The drainage area of the Colorado River is divided into Upper and Lower Basins at Lee Ferry on the main stem about 10 miles south of the Utah-Arizona line. The Upper Basin contains about 70 million acres, excluding the Great Divide Basin, an area of about 2½ million acres of internal drainage in southern Wyoming. The Lower Basin is about 90 million acres, including several small closed basins in Arizona, New Mexico, and Nevada, and some small areas in southern Arizona and southwestern New Mexico that drain south into Mexico.

Export water is diverted at numerous places from tributaries in the Upper Basin to portions of Colorado and Utah outside the Colorado drainage system, and from the lower main stem to southern California.

Renewable water resources in the Colorado River Basin derive from rain and snow which, on the average, contribute about 190 million acre-feet (maf) (14.2 inches) annually to the land surface. Most of the water returns to the atmosphere by evaporation and transpiration, leaving only about 9% (1.4 inches) or 18 maf to feed streams and recharge groundwater. Although precipitation averages 15.7 inches in the Upper Basin and 13 inches in the Lower Basin, it is not evenly distributed, being concentrated in the mountains (figs. 2 and 3). The portion yielded as streamflow (table 1) is more than five times greater in the Upper Basin (16% or 2.5 inches) than in the Lower Basin (3% or 0.4 inches). Overall, three-fourths of the water comes from less than 15% of the land area.

Streamflow is concentrated in spring and early summer when the snow melts. Also, flows vary greatly from year to year as a result of variable precipitation. At Lee Ferry, annual undepleted yields from the Upper Basin have varied from 37% to 163% of the 83-year mean flow of 14.7 maf (fig. 4). Undepleted yields from Lower Basin tributaries combined average only 3.1 maf/yr, but yearly amounts fluctuate much more than in the Upper Basin. Further, multiyear periods of persistent below or above average yields have occurred. Because of these extremes in water yield, storage facilities are necessary to fully utilize water resources, especially additional water from vegetation management, because the increases are largest in wet years when flows already are high. Major reservoirs on the Colorado River and its tributaries provide usable storage for about 32 maf in each of the Upper and Lower Basins. When full, these reservoirs hold nearly four times the annual water yield of the entire Colorado River drainage area. In some headwater areas, however, seasonal deficiencies in water supply may develop because of inadequate facilities to store spring runoffs.

The Colorado River Compact in 1922 apportioned 7.5 maf/yr of Colorado River water for consumptive uses in the Upper Basin and 8.5 maf/yr in the Lower Basin, and obligated the Upper Basin to release no less than 75 maf to the Lower Basin every 10 years. An additional later commitment guaranteed 1.5 maf/yr to Mexico, with the stipulation that both the Upper and Lower Basins are to share equally in meeting the Mexican treaty obligation if there is insufficient water surplus to the 16 maf/yr of apportionments. These did not appear to be unduly

5/ Ffolliott, Peter F., and David B. Thorud. 1975. Water yield improvement by vegetation management: Focus on Arizona. School of Renewable Natural Resources, University of Arizona. Available by accession no. PB-246-055 from National Technical Information Service, U.S. Department of Commerce, Springfield, Va. 22161.

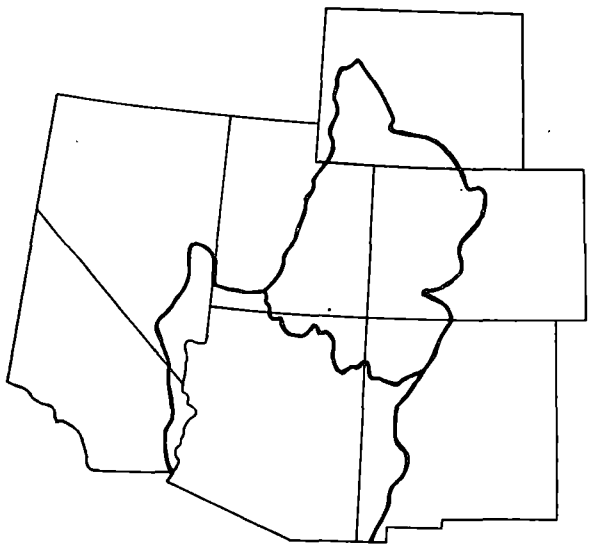

Figure 1.--Upper and Lower Basins of the Colorado River.

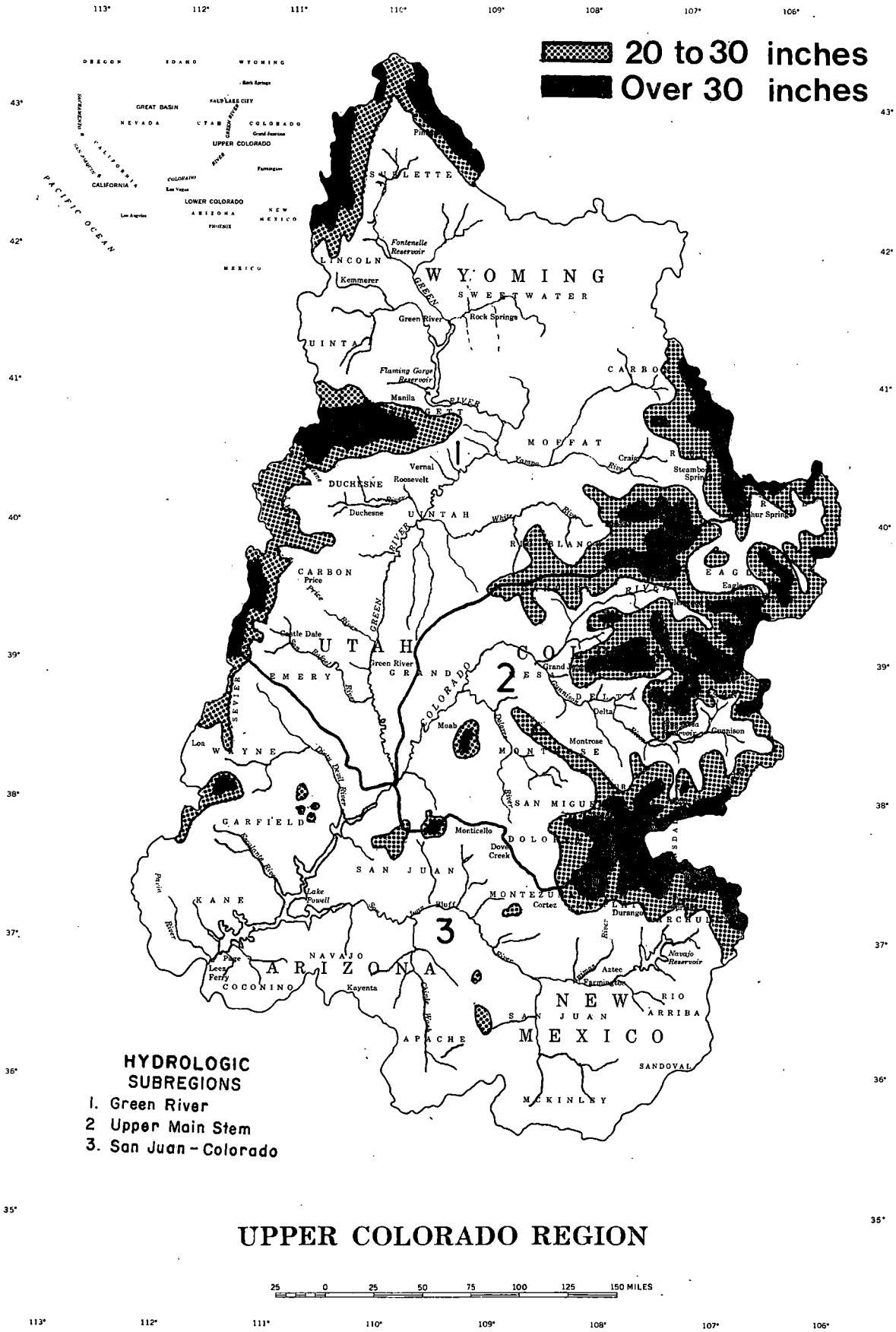


Figure 2.--Precipitation distribution in the Upper Colorado River Basin.

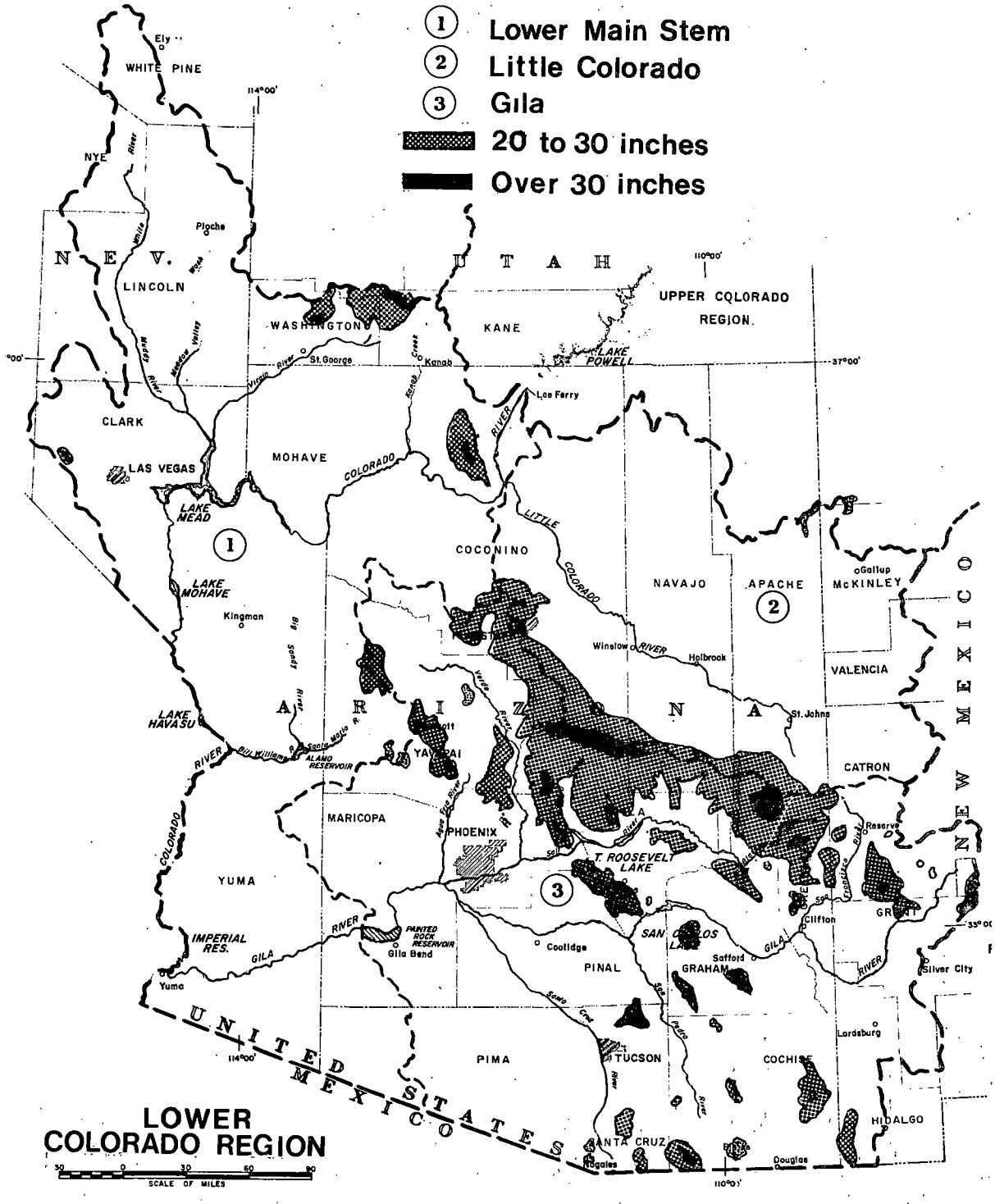


Figure 3.--Precipitation distribution in the Lower Colorado River Basin.

Table 1.--Colorado River undepleted [1/] water supply (1914-1965).
Source: Upper and Lower Colorado Region Comprehensive Framework Studies (PSIAC 1971a, 1971b).

| | Size of contributing area (M acres) | Percent of basin area | Annual water yield (M acre-ft) | Percent of basin yield |
|---|---|---|---|---|
| UPPER BASIN | | | | |
| Green River | 28,636 | 41 | 5,460 | 37 |
| Upper Main Stem | 16,763 | 24 | 6,806 | 46 |
| San Juan-Colorado | 24,732 | 35 | 2,606 | 17 |
| Subtotal | 70,131 | 100 | 14,872 [2/] | 100 |
| LOWER BASIN | | | | |
| Lower Main Stem | 36,195 | 40 | 900 | 29 |
| Little Colorado | 17,265 | 19 | 420 | 13 |
| Gila | 36,868 | 41 | 1,800 | 58 |
| Subtotal | 90,328 | 100 | 3,120 | 100 |
| TOTAL COLO. RIVER | 160,459 | | 17,992 | |

[1/] Undepleted or virgin flow is the flow that would occur without withdrawals for agriculture and other uses and reservoir evaporation.

[2/] Upper Basin depletions normalized for 1965 reduce the outflow at Lee Ferry from 14,872,000 to 11,421,000 acre-feet. Depletions include irrigation 2,128,000; export 550,000; other uses 130,000; and reservoir evaporation 643,000.

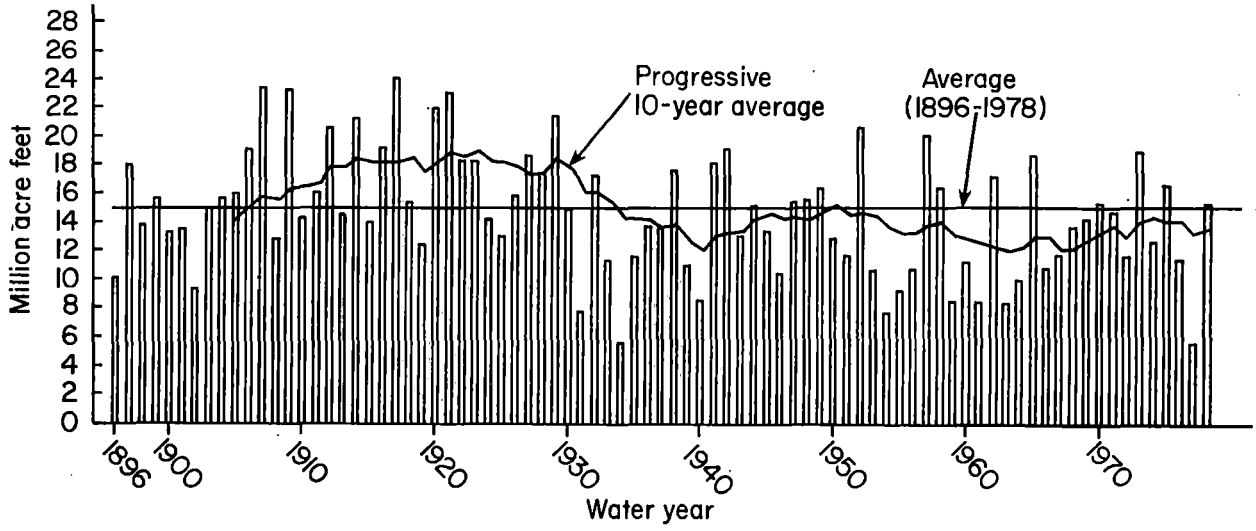


Figure 4.--Annual undepleted (virgin) flows of the Colorado River at Lee Ferry, Ariz., 1896-1978.

large demands on the Colorado River supply, since the Upper Basin alone produced an average of 16.8 maf/yr for the 26 years of record prior to 1922.

Since then, however, undepleted flow at Lee Ferry has averaged less than 14 maf, which many believe is about all that can be expected. Long-term streamflow records, reconstructed from tree rings by Stockton and Jacoby (1976), indicate that for the past 450 years, flow at Lee Ferry has averaged 13.5 ± 0.5 maf. Their analysis showed that only one other period, the early 1600's, was as wet as the first 30 years of this century.

While present mainstream water uses of about 12 maf/yr in both Upper and Lower Basins are below the long-term trend in average annual water supply, this supply is less than the apportionments and the Mexican delivery obligation. Future water needs for development of the Basin's energy resources and other uses have been forecast to exceed supplies by about the year 2000.

Estimates of Colorado River water annually available for consumptive uses within the Upper Basin differ with varying interpretations of Compact provisions and assumptions about future water supply. Generally, the Compact apportionment of 7.5 maf/yr for Upper Basin use would be depleted by the Mexican delivery obligation, reservoir evaporation, and other depletions to about 5.8 maf/yr, assuming no surpluses. Consumptive utilization in 1974 totaled about 3.7 maf/yr, some 2 maf less than the surface supply available to the Upper Basin. Ground water also is available in the Upper Basin but to date has not been utilized to the extent that it has been in the Lower Basin.

Water annually available for use in the Lower Basin states includes an average of 7.5 maf released by the Upper Basin under terms of Colorado River Compact, 3.1 maf of surface water produced from watersheds within the Lower Basin (table 1), and ground water pumped from within the Lower Basin. The U.S. Supreme Court apportioned the first 7.5 maf available from the Upper Basin for consumptive use in the Lower Basin as follows: California 4.4 maf; Nevada 0.3 maf; and Arizona 2.8 maf, not all of which is utilized by Arizona until the Central Arizona Project is complete. Of the 3.1 maf/yr of natural production within the Lower Basin, much of it is used in Arizona, mostly in the Gila subbasin. Additional large amounts of water are pumped from ground water to supply agriculture and municipal-industrial needs. Ground water overdraft in the Lower Basin currently averages nearly 2.5 maf/yr. To sustain the current use rate within the Lower Basin will require continued overdraft of ground water, even with completion of the Central Arizona Project, unless the water supply can be augmented.

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[6] USDI, Water for Energy Management Team, Report on Water for Energy in the Upper Colorado River Basin. 1974. 71 p.

## Principles of Increasing Water Yield by Management of Vegetation and Snow

Water yield, as used here, is water that derives from precipitation and flows directly off the land surface or through subsurface paths to streams, and to some extent, to ground water aquifers. In the Colorado River Basin, most of the water comes from melting snow that seeps into the ground and percolates downslope until intercepted by stream channels, although some water may enter regional ground water systems and not return to the surface within bounds of the contributing area. Usually, streamflow gaging provides reliable measure of water yielded by areas upstream from gaging sites. Therefore, the terms streamflow and runoff are synonymous with water yield unless otherwise stated.

Water yield (precipitation minus evapotranspiration) may be expressed in the following ways, depending on how the information is used:

1. Ratio or percent of precipitation falling on the contributing area.
2. Depth of water if spread uniformly over the contributing area, usually expressed in inches or metric equivalents, as are precipitation and evaporation. Depth in inches (area inches) is the term most commonly used in this paper to express water yield.
3. Volume measurement such as gallons, cubic feet, or acre-feet.
4. Volume per unit area such as cubic feet per square mile or acre-feet per acre.
5. Any of the above expressed as a rate such as inches per day, cubic feet per second, or acre-feet per acre per year.

Water yield improvement, as it pertains to forest and rangelands in the Colorado River Basin, is based on the premise that streamflow and/or ground water are increased by an amount equal to the net reduction in evapotranspiration from altering vegetation and manipulating snow (Anderson et al. 1976).

Vegetation is controlled largely by climate. Areas of low rainfall dominate the Lower Basin, where vegetation is sparse and drought resistant. Precipitation generally increases with elevation and latitude, until at mid to upper elevations, brush, pinyon-juniper and associated types are replaced by forests. Eventually, the forests give way to the cold, harsh climate of the alpine zone, where only low growing forms of vegetation survive. Precipitation varies from less than 5 inches annually in the lower deserts to more than 50 inches at the higher elevations in the Upper Basin (figs. 2 and 3). Potential evapotranspiration tends to be inversely related to precipitation, because energy for evaporation declines with increasing elevation, latitude, and cloudiness. Water yield, therefore, increases rapidly with precipitation, from near zero in the deserts to as much as 40 inches in the alpine areas.

The potential for increasing water yield by vegetation management is greatest where large reductions can be made in water used by plants. Little opportunity exists to reduce transpiration where precipitation is less than about 18 inches and is exceeded by potential evapotranspiration (warm, dry portions in fig. 5). Because rains do not penetrate far into the soil, one cover type is about as efficient as another in using available water.

At the other extreme (cold, wet climate), the opportunity to decrease transpiration is limited because plants use little water and further reductions are difficult to obtain. The greatest opportunity exists where precipitation exceeds 18 inches and potential evapotranspiration (determined by the Thornthwaite method) exceeds 15 inches. This kind of climate promotes vigorous growth of vegetation capable of using large amounts of water. Modifying cover under these conditions can substantially increase water yield. Riparian vegetation represents a special situation because of water available to plants in addition to natural precipitation in areas where the potential for evapotranspiration is often high.

The best opportunity to increase water yield by snow management is in cold climates where blowing snow can be concentrated in forest openings or trapped in large drifts to reduce evaporation.

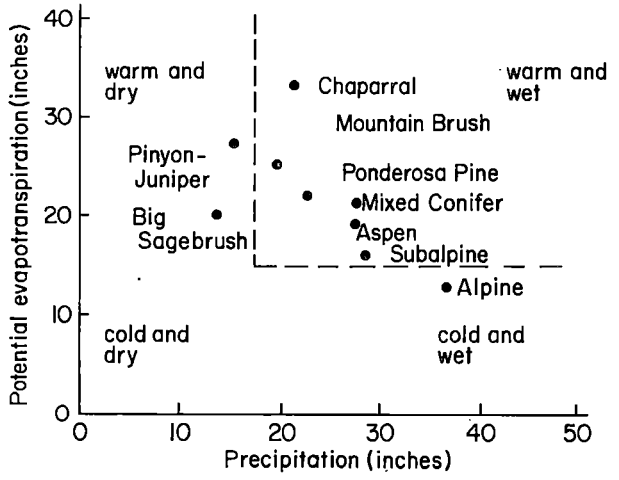


Figure 5.--General relationship of vegetation to potential evapotranspiration (PE) (Thornthwaite and Mather 1957) and precipitation (P) in the Colorado River Basin. The ranges in PE and P are broader than indicated by the average values plotted for each vegetation type. Aspen, for example, overlaps the area between ponderosa pine and subalpine. The dashed lines represent approximate marginal conditions for improving water yield by manipulation of vegetation; the potential is greater in the direction of warm and wet climate.

Vegetation can be managed in several ways to reduce evapotranspiration:

1. Reduce stand density by various practices to reduce transpiration and interception.
2. Convert from one cover type to another that uses less water (type conversion).
3. Create openings in forest cover to reduce transpiration and to redistribute snow, concentrating it to reduce evaporation and increase snowmelt contribution to streamflow.
4. Establish trees or large shrubs in windswept, treeless areas to pile snow in large drifts, thereby reducing evaporation.

Snow management can save considerable water (Tabler 1973). As snow particles are blown by wind in open terrain, they undergo significant evaporation (sublimation) loss and may completely sublimate after being transported a few thousand feet. By trapping snow behind natural or artificial barriers, such as snow fences, evaporation is reduced, and snowmelt water is concentrated to enhance its delivery to the stream. In the forest, specific management practices can be used to promote redistribution of snow by wind from uncut areas of the forest to specially designed openings where more of the snow melts and contributes to streamflow than if snow is uniformly distributed over the entire forested area.

The method of treatment will vary with vegetation type, climate, soils, and topography, and with social, economic, and environmental considerations. Clearcutting and type conversion usually produce maximum increases in water yield compared to thinning and patch cutting. An exception to this may be in areas of heavy snowfall where patch cuts or strip cuts of appropriate size and spacing appear more efficient than large clearcuts (Leaf 1975a).

Thinning, the uniform reduction of forest cover, is probably the least effective method of increasing water yield in the Colorado River Basin, where summer moisture usually falls short of plant water demands. As soil water is depleted during the growing season, plants compete for available moisture. Plants that remain after thinning are capable of using additional water if removal of nearby plants makes it available (fig. 6). As a general rule, uniform thinning of forest and brush stands in the Rocky Mountains and Southwest must exceed 50% before water yield appreciably increases. For this reason, silvicultural systems that use shelterwood or individual tree selection methods of harvest are not as water productive as harvest systems that create openings in the forest cover.

Type conversion, the permanent replacement of one cover type with another, may be appropriate in several vegetation types. In addition to increased water yield, other benefits, such as increased forage and reduced fire hazard, may accrue. However, other resources,

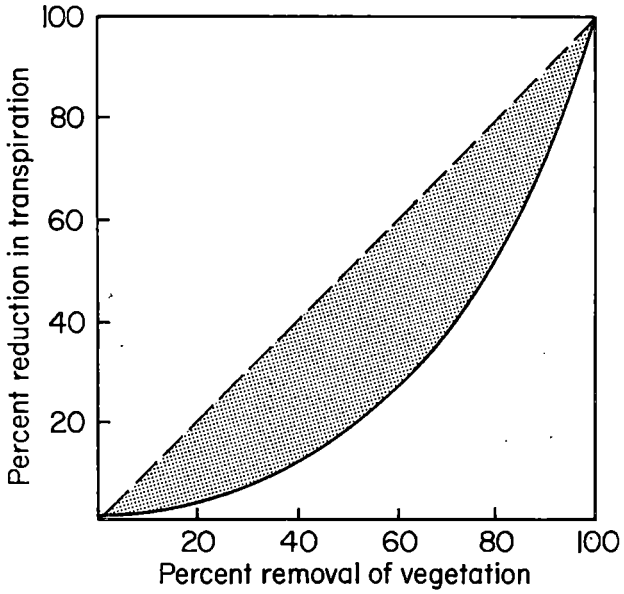


Figure 6.--Hypothetical reduction in transpiration as a function of uniform removal (thinning) of trees and shrubs under conditions that vary from unlimited soil water availability to plants (shaded portion trending toward broken line) to definitely limited availability (shaded portion trending toward solid line).

such as timber, food and cover for wildlife, scenic values of the landscape, and soil stability, require consideration in resources management decisions.

## Combined Effects of Weather Modification and Vegetation Modification

The greatest potential for weather modification in the Colorado River Basin is in the enhancement of precipitation in the mountains, mostly to increase winter snowpack. Atmosphere scientists involved in weather modification generally agree that snowfall can be increased in mountainous regions by 5% to 30%, with 10% an average prediction based on current technology[7/]. A 10% increase in mean winter precipitation in the mountainous area of the Colorado River Basin could add 1 to 4 inches of water in the snowpack. Weather modification will increase streamflow, but the response will vary according to local climate. Lumb and Linsley (1971) determined that, in humid regions, more than 90% of the added precipitation becomes runoff, whereas under semiarid conditions, less than 50% runs off. Most potential target areas for cloud seeding within the Colorado River Basin are between semiarid and humid; thus, it seems likely that, on the average, at least half the additional precipitation will become runoff. However, in the Lower Basin, the portion may be less.

Substantial increases in water yield have been estimated for the Colorado River Basin, based on projected results of weather modification. The USDI Bureau of Reclamation[8/] estimated a potential increase in runoff of 1,315,000 acre-feet per year for the Upper Basin from cloud seeding efforts on some 13 million acres of high mountain lands. The runoff increase is equivalent to an average depth of 1.18 inches over the target areas, which cover approximately 19% of the Upper Basin. In the Lower Basin, only the Mogollon Rim area, including headwaters of the Verde, Salt, and Gila Rivers, all within the Gila Basin, was considered seedable. The potential for increasing runoff on this area (5%

7/ PSIAC Water Management Subcommittee. Herbert B. Osborn, chairman of task force report: "State-of-the-art in weather modification in the Pacific Southwest." April 1977. 10 p.

8/ USDI Bur. Reclama., Div. Atmos. Water Resour. Manage., Westwide Study Manage. Group, Western U.S. Water Plan, " Augmentation Potential through Weather Modification: A Working Document." February 1975. 51 p.

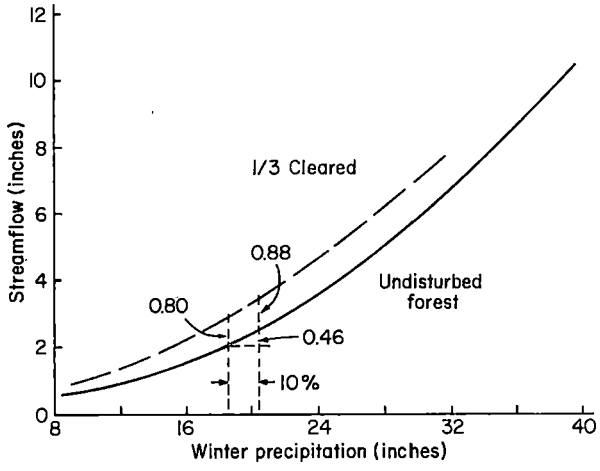


Figure 7.--Relationship of water yield to winter precipitation in a mixed conifer forested watershed (248 acres) before and after clearing one-third of the watershed and converting to grass. Assuming a 10% increase in mean winter precipitation from weather modification, the synergistic interaction results in an 0.88-inch increase in streamflow, or 10% more than the 0.80-inch expected without weather modification. Weather modification alone would increase water yield by 0.46 inch.

of the Lower Basin) was estimated at 239,000 acre-feet, equivalent to 0.6 inch of water if spread uniformly over the 4.7 million acres of target area.

The combined effects of weather modification and vegetation modification can be expected to increase water yield more than if the two practices are applied separately (Satterlund 1969). This concept is illustrated in figure 7, which shows the relationship between water yield and winter precipitation on an experimental watershed in the mixed conifer type in central Arizona (Rich and Gottfried 1976). Curves have been fitted to before- and after-treatment periods, (each containing years of above average and below average precipitation) to show the effect on streamflow of clearing one-third of the watershed.

Assuming a 10% (1.86 inches) augmentation of mean winter precipitation, the incremental increase in streamflow from the watershed without treatment is 0.46 inch (the depth of the water if spread uniformly over the watershed), or 25% of the additional precipitation. If treatment to reduce vegetation is applied in addition to weather modification, the expected water yield increase is 0.88 inch, which is a 10% improvement in treatment efficiency over the 0.80-inch increase expected from treatment without weather modification. Perhaps a more meaningful evaluation compares the sum of the two practices if they are applied separately (0.46 + 0.80 = 1.26 inches) with the sum of the combined effect (0.46 + 0.88 = 1.34 inch). The quantitative gain is the same (0.08 inch), but the percentage gain is 6%.

Satterlund (1969) simulated simultaneous application of cloud seeding and vegetation modification at 30 sites in the United States known to support woody vegetation. By assuming a uniform 10% increase in precipitation from cloud seeding, and reductions of 10% and 25% in evapotranspiration from two levels of vegetation modification, Satterlund found that a synergistic effect was indicated in nearly every case, except at the driest and wettest extremes. Increased runoff attributable to synergistic interaction ranged from 0 to 1.7 inches annually, with quantities exceeding 1 inch annually appearing commonly from wooded regions of the dry Southwest. For the most part, however, the synergistic gains were less than one-half inch, or 5% to 10% greater than if the two practices were applied separately.

The synergistic gain from combining weather and vegetation modification can be expected to vary within the Colorado River Basin, although perhaps less so than was found by Satterlund nationwide. While in some cases the synergistic effect may be small or insignificant, there is no basis for assuming a negative interaction. Thus, there is justification for combining the practices when possible, since, by doing so, the potential to increase streamflow may improve 5% to 10%, or more in some situations.

## Summary of Potential Increases

Eleven cover types were delineated based on differences in water response to treatment. These cover types are alpine, mountain grasslands, subalpine, mixed conifer, aspen, ponderosa pine, chaparral, mountain brush, big sagebrush, pinyon-juniper, and upstream riparian. Phreatophytes along downstream portions of the major rivers were not included. These 11 cover types occupy some 76 million acres in the Colorado River Basin, nearly one-half of the total area (tables 2 and 3). However, about 50 million acres are classified as sagebrush and pinyon-juniper, which have little or no potential, except on exceptional sites. Thus the focus is on about 26 million acres, or 16% of the entire basin. Of these, more than 18 million acres are forested (conifers and aspen in tables 2 and 3), of which about 15 million acres are classified as commercial forest (table 4).

Subalpine forests consisting of spruce, fir, lodgepole pine, and Douglas-fir (table 4) are the major sources of timber in the Upper Basin. Ponderosa pine is the largest source of timber in the Lower Basin, followed by mixed conifer forest species (spruce-fir and Douglas-fir in table 4). Aspen is currently a minor source of wood products, although it will probably be used more extensively in the future, particularly in the Upper Basin where most of the aspen is found.

Commercial forests are 78% public owned in the Upper Basin and about 70% in the Lower Basin. National Forest lands account for more than two-thirds of commercial timber in each Basin, but the portion on Indian lands is much greater in the Lower Basin, as indicated in the following tabulation.

| | UPPER BASIN | LOWER BASIN |
|---|---|---|
| Natl. For. | 72% | 69% |
| BLM | 5% | <1% |
| Indian Trust | 4% | 23% |
| State & County | 1% | 1% |
| Priv. & Corp. | 18% | 7% |

Ownership patterns also change with forest type. Spruce-fir forests are about 80% under National Forest administration, while ponderosa pine forests are less than 69% managed by this agency.

Estimates of potential water yield increases are summarized in tables 5 and 6 for Upper and Lower Basins of the Colorado River. The data are presented as ranges of average onsite increases in area inches (water uniformly distributed over the treatment area). In commercial conifer forests--subalpine, mixed conifer, and ponderosa pine--treatment area refers to the entire working area where timber harvesting or other management practices are applied, including intervening trees, shrubs, or open areas which may receive some type of silvicultural treatment, or are left undisturbed. However, in the aspen, brushlands, pinyon-juniper, and

Table 2.--Land ownership by vegetation type (thousands of acres) in the Upper Colorado River Basin. Source: Upper Colorado Region Comprehensive Framework Studies (PSIAC 1971a).

| Administration | Alpine | Conifer | Hardwood (Aspen) | Woodland (P-J & Oak) | Brushland (Mountain brush) | Desert shrub & grassland | Other | Totals |
|---|---|---|---|---|---|---|---|---|
| GREENRIVER SUBBASIN[1/] | | | | | | | | |
| Forest Service | 352 | 2,136 | 856 | 163 | 293 | 860 | 5 | 4,664 |
| Other | 2 | 758 | 256 | 3,386 | 1,033 | 18,815 | 2,087 | 26,337 |
| Subtotal | 354 | 2,894 | 1,112 | 3,549 | 1,326 | 19,675 | 2,092 | 31,002 |
| UPPER MAIN STEM SUBBASIN | | | | | | | | |
| Forest Service | 804 | 2,854 | 1,223 | 22 | 553 | 532 | 15 | 6,002 |
| Other | 1 | 624 | 335 | 3,167 | 1,193 | 3,787 | 1,591 | 10,699 |
| Subtotal | 805 | 3,478 | 1,558 | 3,189 | 1,746 | 4,319 | 1,606 | 16,701 |
| SAN JUAN SUBBASIN | | | | | | | | |
| Forest Service | 158 | 1,357 | 230 | 515 | 135 | 257 | 84 | 2,735 |
| Other | 12 | 566 | 282 | 5,318 | 126 | 13,213 | 2,278 | 21,796 |
| Subtotal | 170 | 1,923 | 512 | 5,833 | 261 | 13,470 | 2,362 | 24,531 |
| UPPER COLORADO BASIN | | | | | | | | |
| Forest Service | 1,314 | 6,347 | 2,310 | 890 | 980 | 1,649 | 104 | 13,593 |
| Other | 15 | 1,948 | 872 | 11,681 | 2,353 | 35,815 | 5,956 | 58,641 |
| Subtotal | 1,329 | 8,295 | 3,182 | 12,571 | 3,333 | 37,464 | 6,060 | 72,234 |

[1/] Includes Great Divide Basin, an area of about 2.5 million acres of internal drainage in southern Wyoming (mostly desert shrub and grassland vegetation).

Table 3.--Land ownership (thousand acres) by vegetation type in the Lower Colorado River Basin
Source: Lower Colorado Region Comprehensive Framework Studies (PSIAC 1971b).

| Administration | Alpine | Conifer | Hardwood (Aspen) | Pinyon-juniper | Brushland (Chaparral) | Riparian | Desert shrub & grassland | Other | Totals |
|---|---|---|---|---|---|---|---|---|---|
| LOWER MAIN STEM SUBBASIN | | | | | | | | | |
| Forest Service | - | 559 | 56 | 793 | 109 | - | 576 | 20 | 2,113 |
| B. L. M. | - | 41 | - | 3,732 | 94 | 7 | 12,885 | 5 | 16,764 |
| Other federal | - | 205 | - | 956 | 2 | 15 | 7,264 | - | 8,442 |
| State | - | 7 | - | 560 | 167 | 9 | 1,702 | 11 | 2,456 |
| Private & other | - | 201 | - | 867 | 67 | 19 | 2,864 | 380 | 4,398 |
| Indian | - | 55 | - | 488 | - | 2 | 1,213 | 71 | 1,829 |
| Subtotal | - | 1,068 | 56 | 7,396 | 439 | 52 | 26,504 | 487 | 36,002 |
| LITTLE COLORADO SUBBASIN | | | | | | | | | |
| Forest Service | 2 | 1,282 | 23 | 803 | - | - | 237 | - | 2,347 |
| B. L. M. | - | 55 | - | 388 | - | - | 418 | - | 861 |
| Other federal | - | 10 | - | 26 | - | - | 136 | - | 172 |
| State | - | 22 | - | 751 | - | - | 907 | - | 1,680 |
| Private & other | - | 123 | 14 | 1,323 | - | - | 2,566 | 65 | 4,091 |
| Indian | - | 210 | - | 2,318 | - | - | 5,595 | 17 | 8,140 |
| Subtotal | 2 | 1,702 | 37 | 5,609 | - | - | 9,859 | 82 | 17,291 |
| GILA SUBBASIN | | | | | | | | | |
| Forest Service | - | 2,612 | 12 | 4,152 | 1,692 | 50 | 2,090 | - | 10,608 |
| B. L. M. | - | 2 | - | 215 | 416 | - | 4,414 | 15 | 5,062 |
| Other federal | - | 38 | - | 30 | 54 | - | 464 | 29 | 615 |
| State | - | 32 | - | 440 | 353 | 1 | 5,495 | 119 | 6,440 |
| Private & other | - | 74 | 10 | 709 | 350 | 3 | 4,938 | 1,560 | 7,644 |
| Indian | - | 994 | - | 1,352 | 162 | - | 3,822 | 113 | 6,443 |
| Subtotal | - | 3,752 | 22 | 6,898 | 3,027 | 54 | 21,223 | 1,836 | 36,812 |
| LOWER COLORADO BASIN | | | | | | | | | |
| Forest Service | 2 | 4,453 | 91 | 5,748 | 1,801 | 50 | 2,903 | 20 | 15,068 |
| B. L. M. | - | 98 | - | 4,335 | 510 | 7 | 17,717 | 20 | 22,687 |
| Other federal | - | 253 | - | 1,112 | 56 | 15 | 7,864 | 29 | 9,229 |
| State | - | 61 | - | 1,751 | 520 | 10 | 8,104 | 130 | 10,576 |
| Private & other | - | 398 | 24 | 2,899 | 417 | 22 | 10,368 | 2,005 | 16,133 |
| Indian | - | 1,259 | - | 4,158 | 162 | 2 | 10,630 | 201 | 16,412 |
| TOTAL | 2 | 6,522 | 115 | 19,903 | 3,466 | 106 | 57,586 | 2,405 | 90,105 |

Table 4.--Approximate commerical forest acreages (thousand acres) by five forest types in the Colorado River Basin. Source: Upper and Lower Colorado Region Comprehensive Framework Studies (PSIAC 1971a, 1971b).

| Subbasin | Spruce -fir [1/] | Lodgepole pine | Douglas -fir | Ponderosa pine | Hardwoods (mostly aspen) | Total |
|---|---|---|---|---|---|---|
| UPPER BASIN | | | | | | |
| Green River | 730 | 870 | 380 | 90 | 840 | 2,910 |
| Upper Main Stem | 1,550 | 820 | 370 | 360 | 1,440 | 4,540 |
| San Juan-Colo. | 520 | -- | 280 | 800 | 370 | 1,970 |
| Subtotal | 2,800 | 1,690 | 1,030 | 1,250 | 2,650 | 9,420 |
| LOWER BASIN [2/] | | | | | | |
| Lower Main Stem | 110 | -- | 96 | 801 | 56 | 1,063 |
| Little Colorado | 18 | -- | 17 | 1,437 | 37 | 1,509 |
| Gila | 18 | -- | 122 | 3,425 | 22 | 3,597 |
| Subtotal | 156 | -- | 235 | 5,663 | 115 | 6,169 |
| TOTAL COLO. RIVER | 1,956 | 1,690 | 1,265 | 6,913 | 2,765 | 15,589 |

[1/] Spruce-fir, lodgepole pine, and Douglas-fir together make up the subalpine type in the Upper Basin; in the Lower Basin, spruce-fir and Douglas-fir are included in the mixed conifer type.

2/ Lower Basin acreages include about 666,000 acres (mostly ponderosa pine) that, while suitable for timber production, are within the boundaries of National Parks, recreation areas, wilderness areas, high value scenic areas, and similar categories. Thus the total area suitable and available for commercial timber production in the Lower Basin is about 5.5 million acres, and in both basins about 15 million acres.

upstream riparian zones, treatment area refers only to area cleared, converted, or otherwise modified; it does not include surrounding or intervening areas left untreated for wildlife, esthetics, or other purposes. A somewhat different interpretation of treatment area is applied to alpine, mountain grasslands, and high elevation sagebrush lands, where snow management is the water yield improvement method. Under these situations, treatment area refers to the snow source area (fetch) upwind of snow fences or other barriers, plus the downwind accumulation area where the snowdrift forms.

Variations in site capability, climate, and treatment methods determine the range of water yield response in each of the vegetation types (Appendix I). The greatest response in streamflow can be expected on sites where large reductions can be made in evaporation and transpiration, whether this is done by trapping snow or reducing vegetation cover. Clearcutting and type conversion are the methods that usually increase streamflow the most, except in the subalpine zone, where the cutting of small openings in the forest cover is considered most water productive.

The vegetation type that offers the best opportunity for improving water yield in the Upper Basin is the supalpine because of its large acreage and good response to treatment. The next most promising type is aspen, followed by mountain brush and ponderosa pine. In the Lower Basin, the opportunity to improve the water supply is best in chaparral and ponderosa pine. Opportunities in mixed conifer and aspen are limited by the small acreage of these forests.

The potential for increasing water yield per unit area of treatment is greatest in upstream riparian vegetation, and is least in pinyon-juniper and sagebrush lands. However, none of these cover types is likely to be the source of large amounts of additional water. The upstream riparian areas are small and valuable for other uses that are not compatible with treatment practices required to accentuate water yield. Big sagebrush covers large areas in the Upper Basin, and pinyon-juniper is extensive in both Basins, but neither of these shows any promise for improving water yield, except on the most favorable sites. In the alpine and mountain grasslands, the potential is greater. However, the potential increases shown in tables 5 and 6 are projected

Table 5.--Potential and adjusted water yield increases (inches) and total area of each vegetation type, Upper Colorado River Basin.

| | Millions of acres | Potential increase | [1/] Adjusted increase |
|---|---|---|---|
| Alpine | 1.3 | 2 - 5 | |
| Mountain grasslands | unknown | 1.5 - 3 | |
| Subalpine | 6.8 | 1 - 3 | [2/] 1 - 3 |
| Aspen | 3.2 | 3 - 5 | 0.3 - 1 |
| Ponderosa pine | 1.5 | 1 - 3 | .1 - 1 |
| Mountain brush | 3.3 | 1 - 3 | |
| Big sagebrush | 17.6 | 0 - 1 | |
| Pinyon-juniper | 12.6 | 0 - 0.5 | |
| Upstream riparian | unknown | 6 - 24 | |

[1/] Adjustments reflect multiple use and other considerations.

[2/] No reduction was indicated for subalpine forests because patchcutting, which tends to be most water productive, was also considered to be acceptable from multiple use and silvicultural standpoints. Under shelterwood, individual tree selection, or group selection harvest methods, water yield increases probably would be less than one-half these values.

Table 6.--Potential and adjusted water yield increases (inches) and total area of each vegetation type, Lower Colorado River Basin

| | Millions of acres | Potential increase | [1/] Adjusted increase |
|---|---|---|---|
| Mountain grasslands | 0.1 | 1.5 - 2 | |
| Mixed conifer | .4 | 3 - 4 | 1 - 2 |
| Aspen | .1 | 3 - 5 | 0.3 - 1 |
| Ponderosa pine | 6.0 | 1 - 3 | .1 - 1 |
| Chaparral | 3.5 | 1 - 5 | 2.4 |
| Pinyon-juniper | 19.9 | 0 - 0.5 | |
| Upstream riparian | .1 | 6 - 24 | |

[1/] Adjustments reflect multiple use and other considerations.

with uncertainty, being based on increased catch of snow fences on experimental sites, without the opportunity to actually demonstrate, within a watershed, that a net increase in water yield of this magnitude would result from the treatments.

### Adjustments for Multiple Use and Other Considerations

Where clearcutting and type conversion are not acceptable management practices, water yield response to treatment will be less than full potential, depending on the amount and methods of vegetation reduction. The potential increases for the mixed conifer, ponderosa pine, aspen, and chaparral vegetation types were adjusted (tables 5 and 6) to reflect the experience of some units in making adjustments for multiple use and other considerations. Potential increases were reduced by one-half or more in all commercial forest types, except subalpine forests, where patch cutting, which tends to be most water productive, was also considered to be acceptable from a multiple use standpoint. Where patch cutting is not an acceptable method of harvesting subalpine forests, and other silvicultural systems, such as individual tree selection, group selection, or shelterwood methods, are used, the potential for increasing water yield may be less than one-half that expected from patch cutting (Leaf 1975a).

Adjustments for mixed conifer forests reduced the potential increases from a range of 3 to 4 inches down to a range of 1 to 2 inches depth over the area being managed, based on an assumed management strategy of periodic patch cutting that would maintain about one-third of the area in small openings. In the ponderosa

pine, clearing dense stands of trees can increase water yield by 1 to 3 inches over the areas cleared. However, management practices designed to provide an acceptable mix of forest products and other resource values are expected to produce, on the average, water yield increases ranging from 0.1 to 1 inch of additional water per year on the areas so managed, and then only on those areas sufficiently stocked to allow enough reduction in the stand to generate the water savings. The adjustments in the potential increase for aspen forests from a range of 3 to 5 inches down to a range of 0.3 to 1 inch reflects a somewhat arbitrary choice of clearcutting options, one at rotation age of 80 years for wood products (0.3 in. average annual increase for 80 years on the area actually clearcut) and the other at rotation age of 25 years to favor wildlife (1.0 inch average annual increase for 25 years on the clearcut portions). The adjustment in the potential increase for chaparral vegetation from a range of 1 to 5 inches to an average of 2.4 inches on areas actually converted reflects lower onsite efficiency expected from a mosaic pattern of treated and untreated areas, and an estimate of offsite losses in transit to points of use downstream.

The increases are projected as long-term averages that could be sustained indefinitely with maintenance programs. Except for the chaparral, there was no reduction for any offsite transmission losses that might occur.

## Comparison with Previous Estimates by Other Investigators

The results of five studies between 1960 and 1974 are summarized in the Appendix II. The first was a comprehensive evaluation in 1960 by the U.S. Senate Select Committee on National Water Resources. The committee concluded that opportunities for improving water yield by vegetation management appeared favorable on about 15% of the area in the 17 western states, but warned that other resources of the land are involved and consideration must be given to their management and sustained production, as well as water. There was no attempt to quantify, in acre-feet, the amount of additional water that could be produced; in fact, the committee cautioned against this type of application without carefully considering constraints and limitations that, in practice, could materially reduce the estimates that might be derived by applying potential increases in inches to treatable acres (table 11, Appendix II).

In the 11 years after the Senate Select Committee report in 1960, several other evaluations were made of the potential for increasing water yield by vegetation management in the West and Southwest. The most detailed of these studies[9/] was conducted by the USDA Forest Service in 1967 and 1968 to get a first approximation of the potential for improving water yield and reducing sediment yield on National Forest lands in the Southwest, including the Colorado River Basin as a separate part of the analysis. The potentials for increasing water yield were expressed in quantities of additional water (table 13, Appendix II) that could be made available on National Forest lands.

Considering only major multiple use constraints, the estimates were 475,000 acre-feet (958,000 acre-feet if water emphasis prescriptions were applied to commercial forests in the snow zone) for the Upper Basin and 342,000 acre-feet for the Lower Basin. The bulk of the yield increase in the Upper Basin would be produced about equally from type conversion in aspen and from timber harvest in commercial forests. However, if the water emphasis alternative were used, nearly three-fourths of the water would come from commercial forest operations. In the Lower Basin, two-thirds of the potential increases would be derived from type conversion in chaparral and about one-fourth from commercial forest operations.

Except for the 1966 evaluations by Storey and Reigner, the results of the Pacific Southwest Hydrologic analysis were available to the other investigators, whose studies are summarized in Appendix II. The evaluations by Reigner (1970), Storey and Reigner (1971), and Reigner et al. (1969) [10/] (table 12, Appendix II) included areas other than the Colorado River Basin, and are difficult to compare directly with the results of the other studies.

The Upper and Lower Comprehensive Framework Studies (PSIAC 1971a and 1971b) included lands of all ownerships within the Colorado River Basin (table 14, Appendix II). The projected water yield increase for the Upper Basin was 434,000 acre-feet, slightly less than estimated by the Pacific Southwest Hydrologic Analysis (table 7). The Lower Basin estimate was 478,000 acre-feet, excluding phreatophytes. The estimate is 40% more than projected by the Pacific Southwest Hydrologic Analysis,and is attributed to the commercial conifer forests, largely ponderosa pine. The contribution from chaparral was virtually the same in both analyses.

The 1974 estimates by Ffolliott and Thorud are based on low and high treatment options in three vegetation types on lands in all ownerships (table 15, Appendix II). Although small

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[9/] Pacific Southwest Hydrologic Analysis Phase 1. Unpublished reports were prepared by USDA Forest Service Rocky Mountain Region, Lakewood, Colo.; Southwestern Region, Albuquerque, N. Mex.; and Intermountain Region, Ogden, Utah.

[10/] Irvin C. Reigner, Ralph C. Maloney, and E. G. Dunford. 1969. Unpublished report. USDA Forest Service, Washington, D.C.

Table 7.--Summaries of potentially treatable area (thousands of acres) and potential increase in water yield (thousands of acre-feet) for three evaluations in the Colorado River Basin.

| Vegetation type | Upper Basin | | Lower Basin | | Total | |
|---|---|---|---|---|---|---|
| | Treatable acres | Acre-feet | Treatable acres | Acre-feet | Treatable acres | Acre-feet |
| Pacific Southwest Hydrologic Analysis [1] (table 13) | | | | | | |
| Brushlands | 333 | 31 | 1,240 | 237 | 1,573 | 268 |
| Riparian | - | - | 69 | 8 | 69 | 8 |
| Commercial | 5,204 | 209 (692)[2] | 2,663 | 89 | 7,867 | 298 (781) |
| Noncommercial | 1,293 | 235 | 645 | 8 | 1,293 | 235 |
| Total | 6,830 | 475 (958) | 4,617 | 342 | 11,447 | 817 (1,300) |
| Comprehensive Framework Studies [3] (table 14) | | | | | | |
| Brushlands | | | 1,232 | 241 | 1,232 | 241 |
| Riparian | | | 59 | 6 | 59 | 6 |
| Conifer forests | | | 3,172 | 223 | 3,172 | 223 |
| Pinyon-juniper | | | 337 | 8 | 337 | 8 |
| Total | 831 | 434 | 4,800 | 478 | 5,631 | 912 |
| Ffolliott-Thorud [4] (table 15) | | | | | | |
| Brushlands | | | 2,513 | 251-503 | | |
| Mixed conifers | | | 83 | 8-41 | | |
| Ponderosa pine | | | 3,430 | 343-686 | | |
| Total | | | 6,026 | 602-1,230 | | |

[1] Applies only to National Forest lands.

[2] Figures in parentheses are water yield increases from commercial forests in the snow zone when timber harvest is scientifically designed for water yield improvement.

[3] Phreatophytes are excluded from these data.

[4] Applies to all ownership lands in Arizona only.

portions of the Lower Basin in western New Mexico, southern Utah, and southern Neveda are not covered by the Ffolliott-Thorud report, which is for Arizona only, the most important water producing areas are included. Ffolliott and Thorud cautioned that their estimates have a hypothetical structure based on stated assumptions and that under operational conditions many constraints may operate to reduce the stated potentials for increasing water yield. The only constraints they considered were areas of low precipitation and areas in ownerships that precluded treatment, such as National Parks and monuments.

The Ffolliott-Thorud estimates of potential increases in acre-feet are compared in table 7 with Lower Basin estimates by the Pacific Southwest Hydrologic Analysis and the Comprehensive Framework Studies. Their low estimates show that 58% (351,000 acre-feet) of the yield would come from commercial conifer forests, primarily the ponderosa pine, and that the remainder (251,000 acre-feet) would come from chaparral, which is only slightly higher than the other two estimates for the chaparral.

Because the current evaluation in this paper gives potential increases in inches depth per unit area only, and does not attempt to specify acreages actually treatable, the only valid comparisons are with results from the Senate Committee and Ffolliott-Thorud studies, which also are presented in area inches. These comparisons are made in table 8. The 1960 Senate Committee estimates pertain to the Southwest generally and the 1974 Ffolliott-Thorud estimates to Arizona only.

Current unadjusted estimates compare fairly well with the 1960 Senate Committee estimates in the subalpine, mixed conifer, aspen, and pinyon-juniper types, but are considerably higher in ponderosa pine and chaparral. However, the Senate Committee value of 0.5 inch of increased water yield for the ponderosa pine, which was based on then current management practices, is within the range of the adjusted current estimate of 0.1 to 1.0 inch. The higher projection for the chaparral in the current evaluation can be attributed to the favorable outcome of several brush conversion studies of the Ari-

Table 8.--Comparison of current evaluation of potential increases (inches) with other estimates.

| | Current evaluation | U.S. Senate 1960 | Ffolliott & Thorud 1974 (Arizona only) | |
|---|---|---|---|---|
| | | | Low option | High option |
| Subalpine | 1 - 3 | 3.0 | | |
| Mixed conifer | 3 - 4 (1 - 2) | 4.5 | 1.2 | 6.0 |
| Chaparral | 1 - 5 (2.4) | 0.5 | 1.2 | 2.4 |
| Ponderosa pine | 1 - 3 (0.1 - 1) | .5 | 1.2 | 2.4 |
| Aspen | 3 - 5 (0.3 - 1) | 3.0 | included with mixed conifer | |
| Pinyon-juniper | 0 - 0.5 | .25 | Negligible | |

[1/] Figures in parentheses are adjusted to reflect multiple use or other considerations.

zona Watershed Program[11/] completed after the Senate Committee report in 1960. These studies demonstrated good potential for increasing water yield in the chaparral, a fact not previously recognized. Similar tests were conducted in the pinyon-juniper vegetation but they failed to strengthen the early projections for low increases from type conversion in this extensive cover type.

The 1974 estimates by Ffolliott and Thorud are based on low and high treatment options in mixed conifer, ponderosa pine, and chaparral. Treatment in the mixed conifer forests would convert to grass one-third to two-thirds of the area next to stream channels. The low option projection of 1.2 inches of increased water yield from converting one-third of the area appears consistent with the current unadjusted estimate of 3 to 4 inches from complete conversion, since response in this vegetation type appears proportional to area treated. However, the high option projection of 6 inches increase from converting only two-thirds of the forest appears overly optimistic. Treatment options in the chaparral would convert 40% and 60% of the area to grass for increases of 1.2 to 2.4 inches. These projections fall within the range of current estimates of 1 to 5 inches from total conversion (the average on favorable sites is 3.8 inches, adjusted to 2.4 inches for onsite and offsite losses).

In the ponderosa pine, the low option by Ffolliott and Thorud would clear one-third in strip cuts for 1.2 inches and the high option would clear two-thirds in strip cuts for 2.4 inches increase. These are slightly higher estimates but not necessarily incompatible with current unadjusted estimates. However, since the current adjusted estimate of 0.1 to 1 inch is considered more realistic from a management standpoint, the water yield potential in the ponderosa pine is believed to be much less than estimated for the Lower Basin by either the Ffolliott-Thorud study or the Comprehensive Framework study. Also, the acreages considered suitable for treatment in these previous studies may not be available, since much of the ponderosa pine is in poorly stocked condition.

## Assessment

### How Much Additional Water?

It is possible to demonstrate, in theory at least, that some 4 million acre-feet per year of additional water could be generated by managing vegetation in the Upper Basin and about 2 million acre-feet in the Lower Basin. These amounts are obtained by multiplying total acreage times unadjusted average increases for each vegetation type in tables 5 and 6. Such large increases could be obtained only if all areas could be treated solely for increasing water yields, a not very realistic management alternative for these lands.

There are several basic reasons why actual yield increases fall short of the maximum potential:

1. Only a portion of each vegetation type can be treated economically for increasing water yield. The amount of area that can be treated depends on many factors in addition to the demand for water and its value in the market place.
2. Consideration of other resource values and desires of the public tend to reduce both the area and the effectiveness of treatments below that which could be obtained if water yield increases were the main objective of management.

[11/] A cooperative research effort by federal, state, and water user interests was started in the 1950's to investigate the feasibility of increasing water yield in Arizona by management of vegetation (Cortner and Berry 1977).

3. The time frame required for water yield improvement practices to become fully operational is probably in the order of several decades for commercial forests with timber harvest rotation ages of up to 120 years. Less time would be required for noncommercial types, such as chaparral.

In an analysis of this kind, much is expected in the way of quantitative results for water use planning purposes. The question of how much additional water can be produced within a multiple use concept of management is one that both the water user and the land manager would like to see answered. However, until all social, economic, and physical factors are fully recognized and integrated into the solution, only a partial answer is possible.

The water user needs to know the number of acre-feet of water that can be made available and the cost. In contrast, the land manager must decide on resource allocations through a planning process that requires complex interactions with various segments of the public, and he must adhere to management guidelines stipulated by Congress[12/]. He must be free to recognize and apply constraints that go beyond the scope of this study and to modify conclusions and limitations that might be contained in it. Both the water user and the land manager should recognize and deal with the additional question of how the cost of increasing water yield compares with the cost of achieving more efficient delivery and application of water already in the system.

With this understanding of land management decisionmaking in mind, we can proceed by a different approach to assessing water yield potential by determining how much treatment would be required to meet certain water augmentation goals. For example, the proposed Yuma Desalting Plant[13/] on the lower Colorado River will produce up to 42,000 acre-feet per year of highly concentrated reject water, which would not be suitable for agricultural, municipal, or industrial uses. The Lower Basin states are unwilling to lose any water through a desalting plant reject stream because of anticipated future shortages. Therefore, the need arises to augment the existing supply by 42,000 acre-feet to make up the difference. Although vegetation management may not be the appropriate way to get the extra water, it is used here as an example to illustrate the role that vegetation management could play in augmentation of the surface water supply.

The 42,000 acre-feet could be obtained by placing 250,000 acres of subalpine forests in the Upper Basin under management designed for water yield improvement as a major objective. Or, by turning to the chaparral in the Lower Basin, the 42,000 acre-feet could be obtained by converting 210,000 acres of brush to grass. Larger acreages in each case might need to be treated, if water yield improvement practices should fail to adequately accomodate other resource values.

As a second example, suppose it became necessary to augment the water supply of the Colorado River by 750,000 acre-feet (nearly 5%) per year on the average, with no restriction on where in the basin the water should be generated. Since the Upper Basin yields nearly five times as much water as the Lower Basin, it would be consistent to look to the Upper Basin for most of the extra water, say 500,000 acre-feet (3.5% increase), and to the Lower Basin for 250,000 acre-feet (8% increase).

In the Upper Basin, treatments and acreages might be considered as indicated in table 9. The average increases projected for each vegetation type are arithmetic averages of the ranges in values shown in tables 5 and 6, or as described in the sections on vegetation types. Averages of the adjusted values were used for the aspen, mixed conifer, ponderosa pine, and chaparral types. In the Lower Basin (table 10), a larger percentage of the area would have to be treated to get the increases desired.

From these arbitrary examples of hypothetical treatments and acreages it appears that one-half million acre-feet of extra water could be generated in the Upper Basin by committing up to 22% of each vegetation type, except the aspen forests, in which 40% would be treated. The management strategy selected for the aspen type was 80-year rotation clearcut harvest in patches covering 20% of the total area plus 25-year rotation of patch cuts of an additional 20% of the total area. Treatment on 22% of the subalpine forests, including Douglas-fir, would produce 50% of the total increase. Mountain brush and aspen would be the next largest contributors. The increases attributed to the alpine zone and big sagebrush vegetation are projected with less certainty than for the other types because of lack of confirmation that these amounts of water can be generated on a watershed basis.

In the Lower Basin, more extensive treatments would be required to generate 250,000 acre-feet of extra water. Only small increases could be expected from snow management in the mountain grasslands and from patch cutting in the aspen, even if these cover types were fully treated. Likewise, because of the limited acreage of the mixed conifers, the potential for this type is small. Therefore, attention is focused on the chaparral and ponderosa pine forests, where 92% of the expected increase would be generated by treating about 20% of the chaparral and 33% of the ponderosa pine. Again, these acreages may not produce the desired amount of

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12/ Provisions of the Forest and Rangeland Renewable Resources Planning Act of 1974 (88 Stat. 476, et seq.), as amended by the National Forest Management Act of 1976 (90 Stat. 2949, et seq.) (16 U.S.C. 1601-1614).

13/ Reject stream replacement study status report, January 1978, 102 p. USDI Bureau of Reclamation, Lower Colorado Region, Boulder City, Nevada.

Table 9.--Hypothetical treatments and percentage of areas necessary to increase water yield in the Upper Basin by 500,000 acre-feet per year.

| | Millions of acres | Percent treated | Method of treatment | [1/] Average increase (inches) | Increased yield (acre-feet) |
|---|---|---|---|---|---|
| Alpine | 1.3 | 5 | Snow fences at 2,000 feet average spacing | 3.50 | 19,000 |
| Subalpine | 6.8 | 22 | Maintain 1/3 area in small patch cuts | 2.00 | 249,000 |
| Aspen | 3.2 | 20 | 80-year rotation clearcuts with regeneration | 0.33 | 18,000 |
| | | 20 | 25-year rotation clearcuts with regeneration | 1.00 | 53,000 |
| Ponderosa pine | 1.5 | 20 | Reduce to and maintain 60-80 $ft^2$ basal area per acre by patch cuts, strip cuts, thinning | 0.55 | 14,000 |
| Mountain brush | 3.3 | 20 | Type conversion to grass | 2.00 | 110,000 |
| Big sagebrush | 17.6 | 5 | Type conversion to grass combined with snow fences | 0.50 | 37,000 |
| Total | | | | | 500,000 |

[1/] Arithmetic average of adjusted or potential increases shown in table 5, except the aspen, which is explained in the section on aspen.

Table 10.--Hypothetical treatments and percentage of areas necessary to increase water yield in the Lower Basin by 250,000 acre-feet

| | Millions of acres | Percent treated | Method of treatment | [1/] Average increase (inches) | Increased yield (acre-feet) |
|---|---|---|---|---|---|
| Mountain grasslands | 0.1 | 10 | Snow fences at 2,000 feet average spacing | 1.75 | 1,500 |
| Mixed conifer | .4 | 33 | Maintain 1/3 area in small patch cuts | 1.50 | 16,500 |
| Aspen | .1 | 20 | 80-year rotation clearcuts with regeneration | 0.33 | 500 |
| | | 20 | 25-year rotation clearcuts with regeneration | 1.00 | 1,500 |
| Ponderosa pine | 6.0 | 33 | Reduce to and maintain 60-80 $ft^2$ basal area per acre by patch cuts, strip cuts, thinning | 0.55 | 91,000 |
| Chaparral | 3.5 | 20 | Type conversion to grass | 2.40 | 140,000 |
| Total | | | | | 251,000 |

[1/] Arithmetic average of adjusted or potential increases shown in table 6, except the aspen and chaparral, which are explained in the sections on aspen and chaparral.

extra water if the suggested treatment practices should require modification to better accomodate other resource values.

Why not treat a larger percentage of chaparral, since the potential is good for increasing yield and the type is low in commercial value? First, large portions may not be treatable because cover is too sparse or slopes too steep, or because certain areas are classified for other uses such as wilderness. Also, "treatment area" in the chaparral refers to the actual area converted to grass or otherwise modified; it does not include surrounding or intervening areas left untreated for wildlife or other purposes. Therefore, treatment of 20% of the chaparral or mountain brush involves a much larger all-inclusive acreage than one in five, since untreated intervening areas may equal or exceed the acreage actually converted to grass.

Availability of treatable acres is uncertain in all of the vegetation types. The arbitrary selection of treatable acreages used in this assessment should not be construed to mean that these acreages would be available for treatment. Treatable acreages may ultimately prove to be less than these, in which case the projected increases in water yield would also be less, unless the treatments were made more water intensive.

For example, there is some doubt that one-third of the ponderosa pine type is sufficiently stocked and otherwise available for the level of operation suggested here. Low to intermediate stocking levels on about two-thirds of the ponderosa pine type may preclude water yield increases from these areas regardless of the management emphasis, except for clearcutting. Water yield may actually decline on some of these areas if stocking levels are brought up to timber management goals, although thinning dense stands of young trees within these areas could compensate some of the loss. Incomplete inventory data on stand and stocking conditions in the remaining approximately one-third of the area prevents accurate appraisal of treatable acreage.

Also, economic feasibility was disregarded in these choices, which, if considered, might change considerably the arbitrary selection of treatments and acreages shown here.

In areas where precipitation might be increased by weather modification, the efficiency for improving water yield may be enhanced because of the synergistic interaction of the two practices when combined on the same area (see section on combined effects of weather modification and vegetation modification).

## Cost of Producing Additional Water

Few good economic evaluations have been made on the costs of water yield improvement by vegetation management. Costs of initial treatment vary from a few dollars per acre to a few hundred dollars per acre, depending on the type of treatment and type of vegetation. Even then, initial cost figures are of limited value in determining cost of increased water yield, unless long-term maintenance costs are included and properly evaluated over a period of years.

A listing of cost per acre-foot of water increases was included in the study by Reigner et al.(1969) (table 12, Appendix II) for the western United States. Presumably, they represent prices of the mid 1960's and include costs of maintenance required to sustain the yield increases. While some of the water costs were much higher than others, the average cost for 83% of the water increases shown in table 12 was less than $9 per acre-foot. The 1.8 million acre-feet from commercial forest management was estimated at less than $2 per acre-foot additional cost to normal timber harvesting operations. Cost estimates of increased water yield from chaparral were about $20 in California and $18 in Arizona, some of which could be borne by the value of increased forage production as a result of treatment.

A cost analysis by the Pacific Southwest Hydrologic Analysis showed that in the Upper Basin, 62% of increased yields from brushlands would cost between $20 and $50 per acre-foot, with the remainder costing more. These cost figures were adjusted to 1969 prices. In the Lower Basin, water from chaparral was considered less expensive; 64% would cost $10 to $20 per acre-foot, and another 35% would be between $20 and $50. The least costly water would come from commercial forests, although it was more costly in the Lower, than the Upper Basin. In the Upper Basin, 93% would cost less than $2 per acre-foot, while in the Lower Basin, only 24% would cost this amount. Another 65% would cost between $2 and $5 per acre-foot. The most expensive water was from noncommercial forests and riparian vegetation.

Installation costs of treatment were projected at $18 per acre (1965 prices) in the Upper Colorado Region Comprehensive Framework Study, but costs per acre-foot of increased yield were not given. Cost estimates per acre-foot from the Lower Region Framework Study are given in Appendix II. Basically, they are similar to most of the others.

The cost of producing extra water by snow fences in alpine and mountain grassland areas has not been determined. However, some preliminary estimates[14/] indicate that, on favorable sites, additional water might be obtained at costs of $10 to $20 per acre-foot.

A detailed economic analysis of chaparral conversion in the Salt-Verde Basin in central Arizona (T. C. Brown et al. 1974) considered costs and benefits of converting chaparral to grass. Only chaparral on National Forest lands

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[14/] Martinelli, M., R. Tabler, and R. A. Schmidt. 1975. An estimate of snow management potential on Straight Canyon barometer watershed, Utah. 9 p., Unpublished report. USDA For. Serv., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

(850,000 acres) was considered in the analysis. More than 500,000 acres of chaparral were rejected initially as not treatable because they were (1) in wilderness or special-use zones, (2) less than 30% crown cover, or (3) on slopes steeper than 60%. The remaining 333,000 acres in 139 delineated areas met the criteria for conversion. For wildlife needs and to leave the area esthetically pleasing, a maximum of 60% of any delineated area was considered convertible. These constraints further reduced convertible area to 176,000 acres or 21% of the original chaparral acreage.

The costs of converting portions of each area to grass and maintaining the conversion over a 50-year period were compared with the benefits to society in terms of increased water yield and forage for livestock, and reduced costs of fighting wildfires. Annual benefits from Alternative 1 were considered to be (1) 0.21 acre-foot of increased water yield per acre of converted chaparral delivered downstream and valued at $12.50 per acre foot, (2) 0.24 additional animal-unit-month per acre of grazing capacity valued at $6.54 per animal-unit-month, and (3) 34 cents per acre reduction in firefighting costs. The average per-acre annuity benefit ($4.49) minus the annuity cost ($1.98) left a net average annual return of $2.51 per converted acre (all 1972 prices).

Three important assumptions were made for the economic analysis. First, a 6-7/8% discount rate was used. Second, it was assumed that all increased streamflow reaching the Phoenix Valley would be used for increasing agricultural production. Third, it was assumed that the relative position of prices would not change over the long run.

While increased forage and reduced firefighting costs helped to defray costs of conversion and maintenance, the value of the increased water satisfied more than one-half of the total cost. Although the relative inputs from increased forage and reduced firefighting costs varied between areas, it seems reasonable to assume that in areas with a benefit-cost ratio greater than 1, additional water would be produced for less than its valuation of $12.50 per acre-foot (1972 prices).

The value of additional water is difficult to determine because of the complicated nature of water rights and laws governing water use and distribution in the Colorado River Basin. Seldom do economic principles operate freely to determine the price of water. In the above described economic analysis (T. C. Brown et al. 1974), the average value ($12.50 per acre-foot) of additional water delivered to the Salt River Valley included hydroelectric power revenues from water falling through the series of dams in the Salt River above Phoenix. The value of the additional water was based on the assumption that the primary user of any additional water in the Valley, at least to the year 2000, would be the agriculture sector--there being some unmet demand for water to irrigate low-valued feed grain and forage crops. All other, higher valued demands are already met. The marginal value of water (that is, the most the farmer could pay for additional water and still pay variable costs) was estimated at $11.20 per acre-foot (1972 prices) (O'Connell 1972, T. C. Brown et al. 1974).

The value of water may increase relative to other values and costs in the future as ground water depletes and demand for water increases as a result of anticipated population growth and energy development within the Colorado River Basin. In anticipation of future water shortages, the Central Arizona Project (scheduled for completion in the mid 1980's) will deliver Colorado River water to central and southern Arizona at a charge of at least $46[15/] per acre-foot for municipal-industrial users. Since this price reflects willingness to pay, it is suggested that additional water from vegetation management may be equally valuable in certain areas.

### Time Frame for Implementing Water Yield Improvement Practices

Long-range planning would be required to fully implement water yield improvement practices outlined in this report. In slow growing forests of the subalpine zone, harvest rotations are of the order of 120 years, although full water yield potential could be realized sooner than the rotation age of forest trees. However, demand for wood products, physical limitations, and economic constraints, among others, will prevent rapid implementation of water improvement programs. For example, demand for aspen wood products would have to increase manyfold before annual harvest of aspen for this purpose, could reach the level required to sustain the water yield potentials projected in tables 9 and 10. Large increases in demand for aspen products are anticipated (Wengert 1976), but the time frame is 25 to 40 years.

Some water yield improvement practices could be implemented within a few years, however, that would result in almost immediate augmentation of water supplies. Type conversion of brushlands to grass shows particular promise for the Lower Basin, where the potential in the chaparral has been well researched, and is now in the pilot testing phase. Sufficient preliminary

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[15/] In 1974, the Central Arizona Water Conservation District Board set tentative canal side charges for CAP water to M&I users at $32.50 per acre-foot plus $13.50 per acre-foot to cover operation, maintenance, and repair costs (for agricultural users these charges are respectively $2.00 and $13.50). These charges can be expected to increase with inflation and other causes. Barr and Pingry (1977) estimated the required canal side charge to M&I users in 1976 dollars at $51 per acre-foot and the full economic cost at more than $100 per acre-foot, including operation, maintenance, repair, distribution, and treatment costs.

work has already been done on the Salt-Verde Basin in central Arizona to identify potentially treatable areas (T. C. Brown, et al. 1974). Similar economic analyses are needed to identify and verify treatment potential on the remaining chaparral areas in the Lower Basin. Also, studies are needed in the Upper Basin to determine extent and applicability of treatments for the mountain brushlands.

## Public Acceptance of Water Yield Improvement Practices

Public acceptance of water yield improvement practices will depend on how people view the need for more water (basically an economic issue), and on how they perceive the impacts of water improvement practices on the forest environment, including the less tangible resources such as wildlife and scenic beauty. The appearance of an area during and after treatment is an important consideration in land use planning. The job of determining the best mix of forest uses is becoming more complex and difficult as demand increases for forest products and amenities, such as timber and wilderness. Some uses of the forest are compatible with efforts to increase water yield (fig. 12, Appendix I), while others are not. Reducing forest cover improves herbage production and can significantly reduce fire hazard in certain situations. Treatments may be beneficial for some species of wildlife and detrimental for others (Franzreb 1977). While scenic beauty usually suffers following treatment, the site tends to recover toward (and may even exceed) pretreatment esthetic levels (Daniel and Boster 1976). Further, some forest types may best be regenerated by clearcutting, or some other form of stand reduction, that will promote development of vigorous new stands. Protection alone may not be enough to perpetuate the aspen type, for example, which is much admired for its scenic beauty and other values (DeByle 1978). A better understanding of these concepts and problems would contribute toward public acceptance of management practices that might otherwise appear questionable to the casual observer.

The potential for increasing water yield by vegetation management is often greatest where supply exceeds demand, and lowest where demand exceeds supply. Thus, the impetus to manage vegetation for water augmentation may be lacking locally, where support from the public is needed to assure a successful program. This problem, and the legality of claiming rights to additional water generated by vegetation management, could become issues of public concern in the Colorado River Basin.

Neither the water supply nor the potential for increasing it, are evenly distributed within the system. The Upper Basin produces five times the flow of the Lower Basin, and probably has at least twice the potential for increasing flow. Within the Upper Basin, the Upper Main Stem Subbasin covers 24% of the land area, but produces 46% of the water supply (table 1). Based on forest acreage (tables 2 and 4), probably one-half of the potential for increasing yield also is in this subbasin. The situation is similar in the Lower Basin, where the bulk of the surface water supply, and the potential for increasing it, are concentrated in the Gila Subbasin.

Although streamflow has been shown to increase as a result of treatment on numerous small experimental watersheds, there is no assurance that the water yield increases projected here can be physically demonstrated at downstream reservoirs or points of use, even if transmission losses are negligible, since the increased flows may not be detectable by conventional measurement techniques after combining with flows from other sources (Bethlahmy 1974b). Therefore, the amount of water yield increase resulting from treatment must be taken on faith unless special gaging and statistical controls are implemented to prove that the increases have actually occurred.

Pilot studies on watersheds of several thousand acres would help to lessen skepticism on the reality of the increases, and bridge the gap between the small experimental watershed and large-scale water yield improvement projects. The USDA Forest Service is conducting an operation-scale study of multiresource management in ponderosa pine on the Beaver Creek Woods Canyon Experimental Watershed in central Arizona (Carder 1977). A similar study is being initiated in the chaparral, and others are being considered for other vegetation types in both Upper and Lower Basins.

## What We Need to Know

1. Detailed resource inventories are needed to quantify areas suitable and available for treatment in all vegetation types, with priority given to ponderosa pine and chaparral in the Lower Basin and mountain brush in the Upper Basin. For example, much of the original ponderosa pine lands are known to be overstocked, understocked, or nonstocked for optimum timber production. Indications are that water yield would not increase and may actually decline on understocked and non-stocked areas if the stands are improved for timber production. Potentials on overstocked areas are difficult to assess because of insufficient information on size, numbers, extent, and distribution of trees within these stands.
2. Economic feasibility studies similar to the Salt-Verde chaparral analysis (T. C. Brown et al. 1974) in central Arizona are necessary to determine practicability of water yield improvement practices, establish priorities, and gain perspective in how vegetation management compares with other methods of augmenting and conserving the water supply.

3. Better water yield predictive models are needed to assess response to different treatments under variable site and climatic conditions and to improve reliability of economic and resource evaluations. Water yield estimates reported in this paper are generalized averages intended as guidelines only; they may not accurately represent water yield response on specific sites.
4. There is a need to inventory upstream riparian communities to determine composition, vigor, and trend of the riparian species. The information would help to determine management alternatives for riparian areas.
5. Quantify "slippage" between onsite experimentally derived estimates of water yield increases and the amounts that can be expected at points of use downstream. Both onsite and offsite (transmission) losses should be considered.
6. Quantify any changes in water yield from "virgin" or baseline conditions attributable to past harvest and management practices in forests and brushlands. How much of the potential increases (or decreases) in water yield is already being realized?

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APPENDIX I

## Potential Water Yield Increases by Vegetation Types

### Alpine Zone

The alpine zone is that part of the mountains above erect tree growth. In the Rockies, this natural limit varies from about 10,000 feet in Wyoming to about 12,000 feet in southern Colorado, northern New Mexico and Arizona (Martinelli 1975). Land forms vary from gentle to precipitous depending on geology and glacial history of the area. Vegetation consists primarily of low-growing grasses, sedges, forbs, lichens, and dwarf willows on wet sites and stunted conifers on drier sites. Almost all of the alpine zone (1.3 million acres) is in the Upper Basin. In the Lower Basin, only a few thousand acres can be found on the highest mountains. The alpine zone is about 98% under Forest Service administration.

The climate is cold and wet with strong, persistent winds on the ridge crests and summits in all seasons. Summer temperatures seldom reach 70° F, and sub-zero days in winter are fairly common. More than 75% of annual precipitation is snow, which is moved by the wind from exposed sites to sheltered spots where it concentrates in deep drifts. Measurement of precipitation is very difficult because of wind. However, it is known that much of the alpine zone receives 40 inches or more annually, some areas as much as 55 or 60 inches. However, because of uneven distribution of snow, windswept exposures tend to be cold deserts, while protected sites are covered with snow most of the year.

Water yield is high from alpine areas because of the heavy precipitation and relatively low evapotranspiration. Few good streamflow records are available from watersheds entirely within this zone, although two examples cited by Martinelli (1975) suggest a range in mean annual water yield as broad as 23 to 44 inches in terms of depth over the contributing area. Several watersheds in the Colorado Rockies up to 150,000 acres yield between 24 and 29 inches annually.[16/] Since only the upper portions of these watersheds would be in the alpine zone, annual yield as much as 44 inches would be possible for the alpine areas. Typically, streamflow peaks in early summer with about 85% of annual yield between May 1 and July 31, and less that 5% between December 1 and March 31 (Martinelli 1975).

The potential for increasing water yield is good in certain areas where evaporation of windblown snow can be reduced by trapping snow in large drifts. This procedure is most effective when snow fences are built upwind of natural accumulation areas. Martinelli (1975) and Tabler (1974) have described criteria for construction and placement of snow fences for most efficient storage of snow. Where snow trapping is efficient, roughly 60 to 120 feet of fence is required to retain an extra acre-foot of water in the snowdrift at the start of the melt season (Martinelli 1973).

The contributing area (fetch) must be sufficient to supply snow to be trapped. Although there is no shortage of drift snow in alpine areas in most years, Martinelli (1975) suggests at least 500 feet of fetch upwind of the snow fence. Therefore, spacing of snow fences for maximum retention of snow might range from 500 feet to something less than the transport distance, defined as the average distance a snow particle travels before completely sublimating (Tabler 1974). This distance varies with relative humidity and temperature of the air, solar radiation, windspeed, and size of snow particles (Schmidt 1972). However, for areas and conditions where snow management might be applied, the transport distance is probably in the realm of a few thousand feet (Tabler 1975).

Possibly other methods of snow management could enhance water yield from the alpine zone. Concentrating snow in large drifts also delays snowmelt and prolongs summer streamflow at higher levels. This is a particularly attractive aspect of snow management, since summer flows are often critically low for local water users. It is less important to downstream water users if adequate storage is available. Even then, storing water in drifts may be less costly and less wasteful than in reservoirs. Other forms of snow management present similar opportunities to improve quantity and timing of high elevation streamflow. Intentional avalanching might be used to concentrate snow in areas near stream channels where its gradual melt would augment flows throughout the summer. Excess water in wet years might also be diverted from streams and sprayed into the air in cold weather to build artificial glaciers to store water for later use (Martinelli 1975).

Although the alpine zone may not be as fragile as is commonly believed (Webber et al. 1976), it must be managed with care. In addition, most artificial structures, such as snow fences, are easily seen from long distances; therefore, the visual impact of such barriers should be taken into account.

While it appears that in favorable areas of the alpine zone, water in the snowpack can be increased by 5 inches per year, and perhaps more in some areas, the extent of these treatable

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16/ Water yield from National Forest System lands in the Rocky Mountain Region. 25 p. January 1972. USDA Forest Service, Division of Watershed Management, Rocky Mountain Region, Lakewood, Colo.

areas and the portion that could be managed for this purpose are not known. Rechard (1973) estimated that above 6,000 feet in Wyoming about 3.5 million acre-feet of water are lost each year to evaporation from blowing snow. While Rechard felt that a large part of this water might be recovered by strategically placed snow fences, he did not attempt to specify the amount. Again, it is difficult to know how much of the increased snowpack will find its way to the water user downstream.

### Mountain Grasslands

High elevation mountain grasslands and other large forest openings covered by grasses, forbs, and low-growing shrubs provide additional opportunity to increase water yield by snow management. These areas are lower in elevation than the alpine zone; the reason they are treeless is not always clear. Strong winds that blow away the snow and abrade and desiccate young seedlings may prevent trees from claiming some of these areas. Soils, aspect, and poor drainage may account for others. Whatever the cause, these treeless areas are often large, continuous openings, surrounded by, or interspersed with, aspen, subalpine, and mixed conifer forest types. They are usually found above 9,000 feet in the Lower Basin, but may occur at lower elevations in the Upper Basin. As with the alpine zone, these are mostly National Forest lands.

The extent of these areas is uncertain. In eastern Arizona, some 80,000 acres of high elevation grasslands are found in large continuous blocks (Thompson et al. 1976). There are some high elevation grasslands in western New Mexico also. A conservative estimate would place the mountain grasslands in the Lower Basin at 100,000 acres. In the Upper Basin, these areas may be even more extensive, but acreages are not separated in forest surveys from other forest types.

The climate is similar to the associated mixed conifer and subalpine types. However, local climates within the openings may be harsher because of greater exposure to wind and sun. In the Lower Basin, precipitation averages 25 to 35 inches, about one-half snow. In the Upper Basin, precipitation may be greater, and more of it snow. Water yield is estimated at 3 inches (Thompson et al. 1976) and upwards annually, depending on how much of the snow is evaporated and removed by wind.

The potential for increasing water yield is probably not as good as in the alpine zone because of less snow and wind. Thompson et al. (1976) estimated that water yield could be increased by 1.5 to 2 inches if snow could be held where it falls on the high elevation grasslands in eastern Arizona. Perhaps even better response would be possible on areas in the Upper Basin that receive more snow and wind.

Most mountain grasslands and meadows are highly scenic areas, and the visual impact of snow fences should be taken into account. It may be possible, however, to establish windbreaks of shrubs, trees, or other more esthetically pleasing materials that will function effectively and still be environmentally acceptable (Thompson et al. 1976). More research and development is needed in this area before a reliable estimate of overall potential would be possible.

### Rocky Mountain Subalpine Forests

Spruce-fir and lodgepole pine forests characterize the subalpine forest zone in the Upper Basin. Spruce-fir forests are usually a mix of Engelmann spruce and subalpine fir, and they occupy the highest forest environment below the alpine zone. These are the principal tree species above 9,000 feet elevation on north facing slopes, and above 10,000 feet on other aspects. Spruce and fir are concentrated in the Colorado Rockies, and, together make up the largest and most valuable timber resource in the Upper Basin (table 4).

Lodgepole pine is the principal tree species in the Wyoming portion of the Upper Basin. Substantial stands also exist in the Uinta Mountains in Utah and in the northern Colorado Rockies. Lodgepole pine forests cover extensive areas between 7,500 and 10,500 feet elevation, but reach maximum development in the upper montane and lower subalpine zones on south and west aspects between 9,000 and 10,000 feet.

Common associates of subalpine forests are quaking aspen at all elevations and Rocky Mountain Douglas-fir below 8,000 feet. Although it is somewhat drier and warmer than spruce-fir and lodgepole pine habitat types, Douglas-fir habitat type is hydrologically similar to the subalpine forests generally, and for purposes of this report is included in the subalpine zone. Aspen, however, is considered separately because of differences in water relationships and treatment methods.

Thus delineated, the total acreage of the subalpine forests is approximately 6.8 million acres, including about 1 million acres of Douglas-fir. Of this total, approximately 5.5 million acres are considered commercial (table 4).

The climate of the subalpine zone is cool and humid. Winters are long and cold; summers are short and cool. Mean annual temperature is near freezing, and frost can occur at any time. Mean annual precipitation, mostly snow, ranges from 20 to more than 50 inches. Overall, the average precipitation for the subalpine zone in the central Rocky Mountains is estimated by Leaf (1975a) at 28-30 inches and streamflow (water yield) at 12-15 inches or about 45% to 55% of precipitation. However, streamflow, like precipitation, varies greatly, and may range from as low as a few inches on drier sites to as much as 40 inches in the wettest areas. More than 90% of the streamflow is generated by melting snow and is concentrated into a relatively short time in the spring (fig. 8). Little overland flow occurs in any season of the year, and erosion rates tend to be low (Leaf 1975a, Frank et al. 1975).

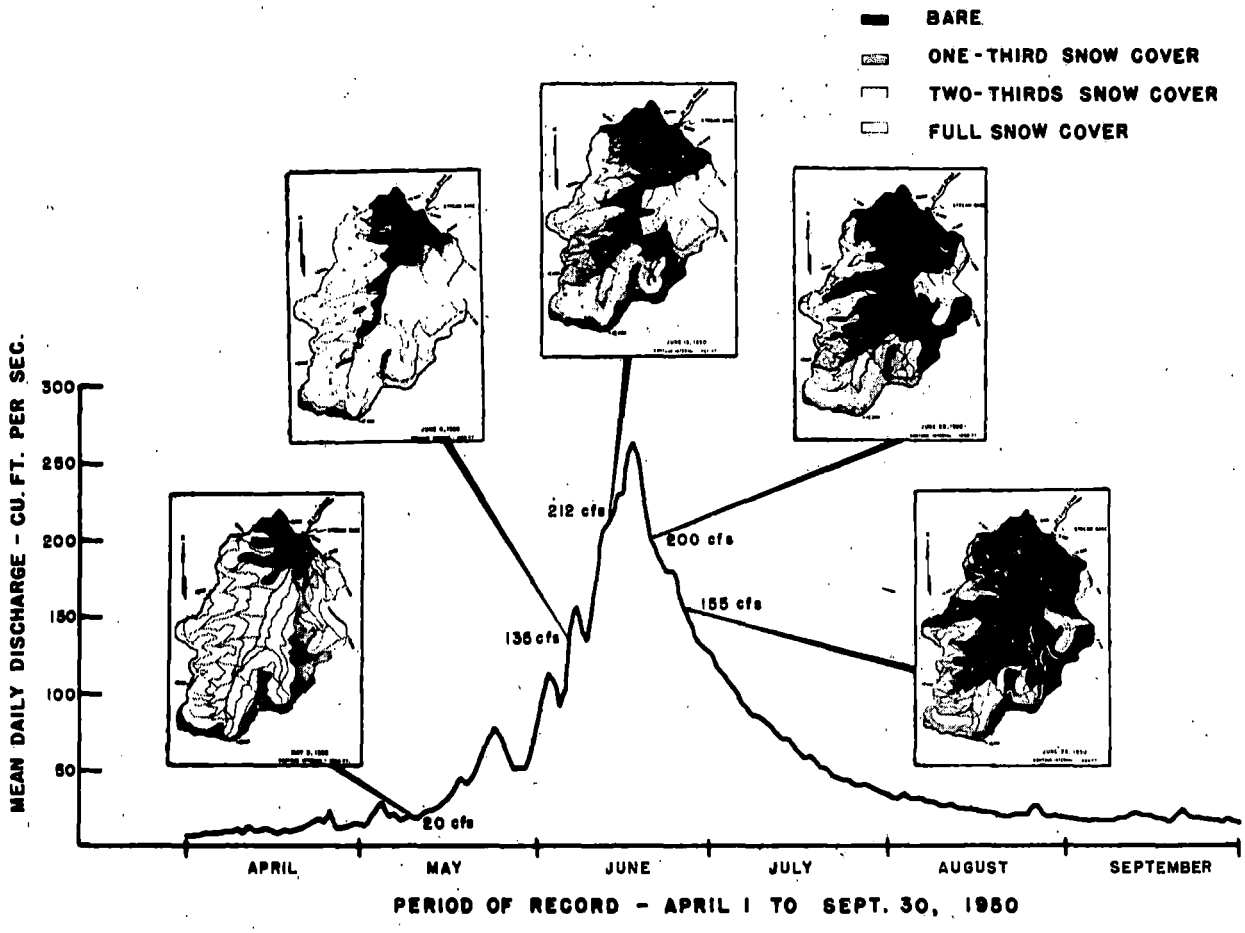


Figure 8.--Snow cover disappearance and snowmelt hydrograph from 32.8-square mile St. Louis Creek near Fraser, Colorado (Alexander and Watkins 1977).

The potential is good for increasing water yield in the subalpine type by managing for snow redistribution and transpiration reduction in small forest openings. Early in this century the classic Wagon Wheel Gap experiment in southwestern Colorado (Bates and Henry 1928) proved that streamflow could be increased by removing forest cover. Natural disruptions in forest stands have produced similar results. A beetle epidemic in the early 1940's near the Continental Divide in Colorado destroyed up to 80% of the Engelman spruce on about one-third of the White and Yampa drainages. As a result of the timber kill, streamflow increased 1 to 2 inches on these drainages, and the increases persisted for many years (Love 1955, Mitchell and Love 1973, Bethlahmy 1974a). Research in subalpine forests in Colorado (Wilm and Dunford 1948; Goodell and Wilm 1955; Goodell 1963; Hoover 1960, 1969, 1973; Hoover and Leaf 1967; Gary 1974; Dietrich and Meiman 1974; Leaf 1975a) and in neighboring areas (Bishop 1961, Ziemer 1964, Herring 1968, Johnston 1975) has shown that while evapotranspiration is decreased when the trees are cut or killed, other factors causing streamflow to increase are also important. These are redistribution of snow from uncut areas to cutover areas (snow blows off adjacent trees and settles in the openings) and the more rapid melting of snow in the cutover areas. The following items highlight the technical aspects of watershed management in the subalpine zone (Leaf 1975a, 1975b).

1. Patch cutting produces the greatest increase in streamflow. Optimum snow redistribution from uncut forest to openings results when openings are: (a) less than eight tree heights in diameter (usually less than 10 acres), (b) protected from wind, and (c) interspersed so that they are five to eight tree heights apart.
2. Snowmelt in patch cut openings on all aspects is more rapid than in the uncut

forest, causing streamflow to be higher on the rising limb of the snowmelt hydrograph than during preharvest conditions. Normally, however, annual flood peaks are not significantly increased if less than 50% of the watershed is cutover in a system of small openings.

3. The pattern and amount of tree harvest determines how much streamflow will be increased. For example, if the forest is removed in large blocks or by selective cutting of individual trees, increases in yield will be less than if the same volume of timber is harvested in small dispersed forest openings.

4. When patch cuts comprise 40% of a densely forested subalpine watershed and 60% is left uncut, annual streamflow may increase as much as 2 to 3 inches over the entire watershed. (If prorated to the patch cut areas only, this amount of increase would be 5 to 7.5 inches). Simulation analyses indicate that there is little difference in response between low-elevation south aspects in lodgepole pine forests and high-elevation north aspects in spruce-fir forests. Hence there is no reason to favor areas of high natural water yield if the objective is to maximize water yield from medium to dense old-growth subalpine forests.

5. Because of the slow regrowth of subalpine forests, increases in water yield diminish very little during the first 20 years. A gradual reduction can be expected after 20 years as the new stand regenerates in the openings, but a decline to pretreatment streamflow may take another 40 years.

Dynamic simulation models have been developed to predict hydrologic impacts of multiple use-sustained yield management practices (Leaf and Alexander 1975). The models are capable of simulating a variety of timber harvesting alternatives. Hydrologic changes and timber yields can be determined for intervals which can vary from a few years to the rotation age of subalpine forest (120 years and longer). This capability provides the manager with the opportunity to examine the probable results of his operations within the context of multiresource objectives.

Three examples of management strategies simulated by Leaf and Alexander are given here to illustrate water yield responses considered feasible in subalpine forests. In one example, the harvest of lodgepole pine in central Colorado was simulated by a series of patch cuts spread over a planning interval of 120 years. At intervals of 30 years, beginning with the first year, approximately one-third of the planning unit would be harvested by clearcutting small openings five to eight times tree height in diameter. By the 61st year, the entire planning unit would be covered by patch cuts. Also, at 30-year intervals, starting 30 years after the old-growth forest on each one-third of the area is patch cut, the regenerated stands are thinned to one-fourth of the natural old-growth forest cover density. At the end of the planning interval, all of the openings will have regenerated and the planning unit (watershed in this case) would contain groups of trees of several age classes from reproduction about 60 years old to stands of timber ready for harvest on the patches first cutover.

Water yield, as projected by the simulation model, would increase after the first cuts and would vary throughout the planning interval because of overlapping effects of the periodic cuts (fig. 9). The average increase in yield for the first 10 years was projected at 1.7 inches per year, but became as much as 3 inches per year for the 10-year interval 61 to 70 years after the initial cutting. The overall average for 120 years was 2.1 inches.

In a second example, also in central Colorado, patch cutting in the spruce-fir type was simulated. The management strategy was similar to that followed in the previous example, except that the patch cuts were spaced at 50-year intervals, because 20 additional years were considered necessary for reproduction to become established. However, the patch cuts would be thinned at 30-year intervals beginning 50 years after each cut. Projected increases in water yield were about one-half those for the lodgepole pine (fig. 9), averaging 1 inch over 140 years.

In a third example, Leaf (1975a) simulated spruce-fir harvest in southwestern Colorado. In this case, the average increase in water yield was projected at 2.3 inches over a 90-year planning interval by patch cutting one-third of the area every 30 years.

From these watershed studies and simulation modeling, it appears that patch cutting in subalpine forests might be expected to increase water yield by 1 to 3 inches on the average over the managed area, depending on site factors and management strategies. However, the amount of

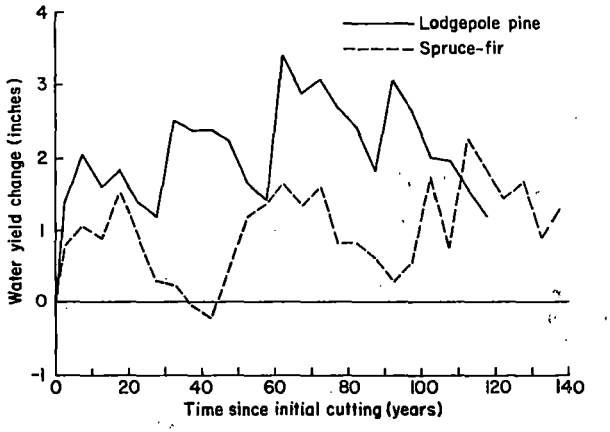


Figure 9.--Projected water yield increases from specific management strategies in lodgepole pine and spruce-fir forests (Leaf and Alexander 1975).

forest land that eventually could be managed in this way can not be readily determined. If all 5.5 million acres of commercial forest land could be put under management strategies to increase water yield by an average of 2 inches per year, the total increase could eventually reach 1 million acre-feet. As a practical matter, this is an unrealistic goal when other forest resources, economics, and social factors are considered.

Current management practices in subalpine forests will produce only small amounts of extra water. The shelterwood silvicultural system is the primary method used in the spruce-fir type. The mature stand of trees is harvested in a series of entries or cuts, usually three, which allow the new stand to develop under cover of a partial forest canopy. The first entry removes from 10% to 40% of the overstory trees, depending on wind and blowdown potential. The second entry is made 10 to 20 years later and may remove 40% to 60% of the remaining volume of trees. The final cut removes the remaining overstory trees, but it is not made until the new stand is present. Water yield is affected little by the early partial cuts, since canopy reduction is more or less uniform (individual tree selection) and is usually less than 50%. Leaf (1975a) predicted that individual-tree selection cutting, in which subalpine forest canopies are reduced 50%, will increase water yield much less than patch cutting--0.4 inch compared to 2.1 inches. Some increase in water yield will probably result from the final overstory removal cut in spruce-fir, although it, too, is considered less efficient than patch cutting.

Water yield can be expected to increase from current timber harvest practices in lodgepole pine and Douglas-fir, since clearcutting and group selection harvest are the favored silvicultural systems for these forest types. The amount of increase depends on the size and distribution of clearcuts in which snow concentrates. If they are too large, wind dips to the ground and scours and blows snow from the openings. The optimum size of opening is five to eight tree heights in diameter, or about 5 to 10 acres, depending on height of the surrounding stand. Clearcuts up to 35 or 40 acres, called for in some timber management plans, may yield less water than smaller openings.

In summary, there is considerable potential for increasing water yield in the subalpine forest. However, to materially improve water yield, greater emphasis would have to be placed on management strategies that favor water production. Although the full potential may not be attainable, since other demands on the forest resource must also be considered, timber harvesting by patch cutting is considered ecologically sound in much of the Rocky Mountain area (Leaf and Alexander 1975), and if done properly, has little impact on water quality. Also, it is a silviculturally acceptable procedure, compatible with guidelines recently developed from research in subalpine forests (Alexander 1974a).

Southwestern Mixed Conifer Forests

Mixed conifer forests in the Southwest occupy a climatic zone between pure stands of ponderosa pine and subalpine forests. The most common overstory species, more or less in order of abundance, are Douglas-fir, ponderosa pine, white fir, Engelmann spruce, aspen, southwestern white pine, blue spruce, and corkbark fir. One or more of these species may be absent in the mix. Most of the mixed conifer type is above 8,000 feet elevation, although some stands can be found below 6,000 feet in canyon bottoms and on protected north aspects. Above 10,000 feet, mixed conifers give way to spruce-fir forests. Ordinarily, stands of Engelmann spruce and corkbark fir or subalpine fir without other species are classified as spruce-fir, but, where they integrate with other conifers, as they often do in the Southwest, they are usually considered part of the mixed conifer type (Jones 1974). Aspen is a closely associated and often intermixed species; for management purposes it is often included with mixed conifer. However, because of differences in water relationships, aspen again is considered separately.

For purposes of this report, all Douglas-fir and spruce-fir forests within the Lower Basin (table 4) are included in the mixed conifer type. All Douglas-fir and mixed conifer within the Upper Basin are included in the subalpine type. The mixed conifer type extends into the San Juan-Colorado subbasin of the Upper Basin, although it is not extensive there. Thus delineated, mixed conifer forests cover about 391,000 acres, all in the Lower Basin. Large openings occur in the type in Arizona, and are considered as mountain grasslands. The commercial value of mixed conifer type is less than ponderosa pine and subalpine forests but more than aspen. Douglas-fir is the most important timber species within the mixed conifer type.

The climate where the mixed conifer type grows is wetter and cooler than in the ponderosa pine type and warmer, though not always drier, than in the higher elevation subalpine type. Precipitation averages from 25 to more than 30 inches per year, one-half or more of it snow. Summer rainfall accounts for a larger part of precipitation in the Southwest than in the central Rocky Mountain area. Because of wetter summers and warmer temperatures, evapotranspiration is greater and water yield is lower than in areas of equal precipitation to the north. Streamflow averages 3 to 5 inches, sometimes more on the wetter sites; three-fourths or more comes from snowmelt.

The potential is good for increasing water yield in mixed conifer forests. Using management strategies similar to those used in subalpine forests, water yield response in the mixed conifer is estimated to be about 25% less than subalpine, although clearcutting large areas appears to increase water yield more than in the subalpine. A possible explanation is that in the drier, warmer climate of the mixed conifer for-

ests, more of the response from altering the cover is attributed to reduction in transpiration and less to redistribution of snow.

Clearcutting experiments on the Workman Creek watersheds in central Arizona (Rich and Thompson 1974, Rich and Gottfried 1976) increased streamflow roughly in proportion to area cleared, while thinning to nearly one-half the original forest basal area increased streamflow very little. Streamflow on North Fork (248 acres) increased 1.3 inches per year on the average after 80 acres (32% watershed) of moist site mixed conifers were cleared and planted to grass. When the cleared area was later expanded to include 100 acres of ponderosa pine on drier sites upslope (combined treatments covered 73% of watershed), the total increase averaged 2.7 inches. Streamflow on nearby South Fork (318 acres) responded only in very wet years to single-tree selection harvest of 45% of the forest basal area (from 201 to 110 sq ft per acre). However, in a subsequent treatment, streamflow increased by 3.7 inches after 83% of the watershed was cleared. When prorated to the areas actually treated, these increases were equivalent to 3.7 and 4.4 inches on North and South Forks, respectively, and averaged 4.1 inches. The streamflow increases have persisted with little or no decline for 10 or more years despite vigorous growth of grasses, forbs, bracken fern, New Mexican locust, and Gambel oak in the cleared areas.

Timber harvest practices on two other experimental watersheds in eastern Arizona have increased streamflow by similar amounts when prorated to the portion of watershed treated. Castle Creek is predominately ponderosa pine, but is adjacent and hydrologically similar to mixed conifer forests (Rich and Thompson 1974). One-sixth of the 900-acre watershed was clearcut in patches fitted to stands of overmature and mistletoe-infected tree classes and areas. The remaining area was selectively harvested to put the stand in good growing condition by reducing the stand basal area from 135 to 63 square feet per acre. Streamflow from the watershed increased 29% (equivalent to a depth of nearly 0.6 inch over the entire watershed) on the average for 10 years. Although some transpiration reduction may be attributed to the thinning, the bulk of the increase in streamflow is believed to have resulted from the clearcut patches, where transpiration reduction, and to a lesser extent snow redistribution, would contribute to water savings.

Another recently completed experiment in mixed conifer on 490-acre Willow Creek watershed in eastern Arizona was designed to evaluate the effects of timber harvest on water yield and timber production. Preliminary results indicate that the treatment, which cleared 58% of the watershed, increased streamflow as much or more than the other experiments.[17/]

[17/] Personal communication with Gerald J. Gottfried, Research Forester, Rocky Mountain Forest and Range Experiment Station.

These studies indicate that the size of openings, at least up to 200 or more acres, is less critical in the mixed conifer type than in the subalpine type, perhaps because of a lesser role played by snow in these more southerly forests. Furthermore, selection cutting or thinning that uniformly reduces the canopy does not appear to reduce evapotranspiration enough to significantly increase streamflow until about one-half of the canopy is removed.

The results of the Workman Creek and Castle Creek experiments were used to develop the relationship in figure 10 (Rich and Thompson 1974), which depicts potential increase in water yield as a function of two variables: percent of watershed in openings and the expected average annual streamflow without treatment. Although Willow Creek data were not used to develop the curves, preliminary results from this watershed fit the relationship very well.

The current status of knowledge in watershed management indicates that if intensive even-aged management were practiced on mixed conifer and Douglas-fir forests, water yield would increase by about 1.5 inches annually (Rich and Thompson 1974). Intensive, even-aged management implies that the forest would be harvested in a series of patch cuttings, three to eight tree heights in diameter, with one-sixth of the area harvested each cutting cycle of approximately 20 years. By the time one-half the 120-year rotation is reached, one-half the area will have been logged; one-sixth would be in recently cleared patches, one-sixth in 20-year-old reproduction, and one-sixth in 40-year-old pole stands. Each of these areas would be effective to some degree in reducing evapotranspiration and increasing snow accumulation. The combined area of "effective" clearings would be at least 30% of the total working area, enough to increase water yield by 1.5 inches, assuming a normal yield (runoff before treatment) of 4 to 5 inches (fig. 10).

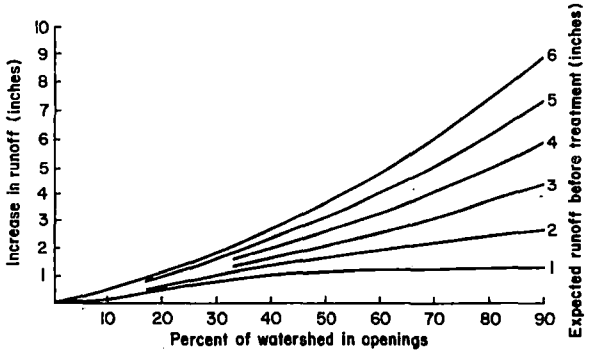


Figure 10.--Potential water yield increase from mixed conifer forests as a function of the percent of watershed in openings 3 to 8 tree heights in diameter and the expected yield without treatment (Rich and Thompson 1974).

While management prescriptions would not necessarily follow precisely the foregoing description, the general approach is compatible with silviculture and management guidelines developed and published in status of knowledge papers by Jones (1974) and Alexander (1974b). As in the subalpine forests, timber harvesting practices such as these can be designed and carried out without seriously increasing erosion or adversely affecting the high quality of water produced by these forests. Effects of wildlife are varied. Timber harvesting (selective overstory removal) in a mixed conifer forest in eastern Arizona proved detrimental to some bird species, but was beneficial to others (Franzreb 1977). Deer and elk habitat can be enhanced by small openings in the forest (Patton 1976), although if the timber harvest were specifically "wildlife oriented", the expected increase in water yield would be less (Brown 1976).

The total increase possible from mixed conifer forests depends on the intensity of treatment and the area treated. If all 391,000 acres were cleared of trees and converted to grass, and if the increase averaged 3 to 4 inches, as found in the clearcutting experiments, possibly 100,000 acre-feet of additional water could be produced annually. Again, as in the subalpine forests, the tradeoffs would be costly. The potential increase would drop below 50,000 acre-feet if the entire area were placed under intensive water-oriented management prescriptions as described for this type. Treatment of fewer acres would correspondingly diminish the extra water that could be produced.

## Rocky Mountain Aspen Forests

Quaking aspen is the most widely distributed tree in North America. This species occupies approximately 3.3 million acres in the Colorado River drainage area, almost all of it in the Upper Basin (tables 2 and 3). Roughly 75% is on National Forest lands. The aspen type is recognized for its multiple values of wood, livestock forage, wildlife habitat, watershed protection, and esthetics; yet, in the West, it has received little management or research attention (Mueggler 1976). Lack of interest in the past can be attributed to weak demand for aspen wood products, although this is likely to change with time, as more attention is focused on commercial aspects of aspen in the Rocky Mountains (USDA Forest Service 1976). About 2,765,000 acres of aspen are classified as commercial (table 4).

Aspen is usually found between 7,000 and 11,000 feet elevation, in pure stands or interspersed among conifers in the subalpine, mixed conifer, and cooler portions of the ponderosa pine type. Aspen is so closely associated with these conifer types, especially Douglas-fir and Engelmann spruce, that it sometimes is included with them for inventory and management purposes, particularly in the Lower Basin, where aspen accounts for only about 115,000 acres of commercial forest land. Further north, in central Colorado and eastern Utah, aspen is much more extensive, and often occurs in pure stands of up to several thousands of acres, where past wildfires have destroyed conifer forests. Aspen has generally been regarded as a fire-induced successional species able to dominate a site by root sprouting until replaced by less fire-enduring and more shade-tolerant conifers. Some aspen stands may be replaced by conifers in a single aspen generation upon curtailment of fire, while in other areas conifer invasion takes much longer (Mueggler 1976). Aspen eventually gives way to a conifer climax if fire is excluded. Since uncontrolled wildfires lack social acceptability, harvesting and controlled burning are considered viable alternatives to prevent aspen from reverting to coniferous forest (USDA Forest Service 1976).

The climate where aspen grows is essentially the same as found in the closely associated lower subalpine and mixed conifer types. Mean annual precipitation ranges from about 20 to more than 40 inches, half or more falling as snow. Water yield also varies greatly depending on precipitation, elevation, and latitude. In the Southwest, water yield averages 3 to 5 inches on most sites, but yield increases with increasing precipitation and cooler climate; some of the wettest aspen sites probably produce upwards of 20 inches as streamflow, judging from data available in the subalpine type.

The potential is good for increasing water yield in the aspen by type conversion. However, increased yields decline rapidly after cutting or other stand reduction practices if regrowth is not controlled. Aspen sprouts profusely after cutting, and within 10 to 15 years, regains its former capacity to use water.

The increases in water yield after clearing are attributed largely to reduction in summer evapotranspiration, although Swanson (1972) working in southwestern Alberta, Canada, found one-third more snow in small openings in aspen stands than in the surrounding closed canopy. The ratio persisted throughout the melt season. Therefore, even though aspen is leafless during winter, redistribution of snow from surrounding forest to small openings may have significance in this type as well as in the subalpine conifer forests.

Research started with the Wagon Wheel Gap study (Bates and Henry 1928), in which average annual streamflow increased by an amount equal to a depth of 1 inch over the entire watershed during 7 years after clearcutting the predominantly aspen cover in 1919. Since that time, several plot studies (Croft and Monninger 1953, Brown and Thompson 1965, Tew 1967a, Johnston et al. 1969, Johnston 1970) have shown that cutting aspen overstory and leaving the herbaceous understory to protect the soil results in reduced soil moisture withdrawals of up to 7 or 8 inches, with the average about 4 or 5 inches. These increased soil moisture levels at the end of the growing season presumably translate to increased water yields during snowmelt, because

less of the melting snow is required to recharge the soil profile, resulting in greater seepage to ground water and streamflow.

The 1-inch increase in streamflow from clearcutting at Wagon Wheel Gap seems low. The treatment there may be properly described as cutting all trees on 84% of the 200-acre watershed, almost three-fourths of which were aspen. By attributing all of the water increase to the portion actually cleared, the increase becomes nearly 1.2 inches, still not as large as might be expected based on more recent studies in aspen and similar vegetation. There appears to be no ready explanation, except that the climate is relatively drier (21 inches precipitation), and the stand is somewhat more open, than other aspen study sites.

In the late 1950's, the USDA Forest Service pilot tested the results of several plot studies by treating part of the aspen cover on 940-acre Sheep Creek watershed in south central Utah.[18/] Elevations on the watershed ranged from 7,790 to 10,360 feet, and precipitation averaged 28 inches between 1957 and 1969. Annual water yield averaged 5.9 inches during 7 pretreatment years. Herbicides were applied over 470 acres, roughly the lower half of the watershed, during the growing seasons of 1965, 1966, and 1967 to kill the forest overstory. Cover on the area treated consisted of 57% aspen, 22% mountain brush, and 21% grasses, forbs, and sagebrush.

The treatment caused major changes in plant composition of all vegetation types in the treated compartment. Grasses increased in percent of ground cover occupied, while most shrubs and forbs were reduced. Streamflow increased by an average amount equal to a depth of 2 inches on Sheep Creek watershed for the 5-year post-treatment period. If attributed to the half of the watershed treated only, the increase was actually 4 inches. It might be concluded that the increase attributable to the aspen and mountain brush portions was even larger, perhaps 5 inches, since these cover types together comprised only 79% of the treated area. Treatment of the grass and sagebrush portion would contribute little to streamflow.

Treatment had no significant effect on yearly peak flows or on water quality. Sediment to the streams decreased as ground cover improved, although mass wasting and related forms of land slippage increased, presumably as a result of wetter soil.

Collectively, plot and watershed studies have shown that water yield can be substantially improved by managing aspen in the Colorado River Basin. DeByle (1976) places streamflow increases at 4 to 6 inches annually for a year or so after clearcutting. Tew[19/] suggests that 5 inches increase is the maximum that can be expected by converting aspen to a grass-forb cover under conditions found in Utah. Investigators agree that if clearcuts are allowed to revegetate naturally, the increase in streamflow will begin to diminish within a couple of years and will disappear within 10 to 15 years (fig. 11). Thus it appears that an initial increase of about 5 inches is the most that can be expected from aspen removal, and if the increase is to be maintained, sprouts must be controlled. Type conversion in the aspen probably would result in a long-term increase of less than 5 inches because replacement cover, once established, is likely to use more water than the herbaceous cover remaining immediately following reduction of the aspen stand. Since there is little information to go on, an arbitrary 3 to 4 inches per year is suggested as the increase that might be maintained from aspen conversion on average sites.

Although the future of aspen remains uncertain, the demand for aspen wood products could expand significantly over the next 25 years (Wengert 1976). Interest in other values, such as wildlife habitat and scenic beauty, can be expected to increase as well. Clearcutting and perhaps controlled burning or other techniques can be used to halt deterioration of aspen stands (Mathison 1976) and thus perpetuate a forest type that is prized for its multiple values (Hronek 1976). If aspen stands are allowed to regenerate naturally after cutting or other methods of stand reduction, the total water increase expected over the 10- to 15-year recovery period (fig. 11) would be about 26 inches (2.2 acre-feet per acre treated). Therefore, if clearcutting for wood

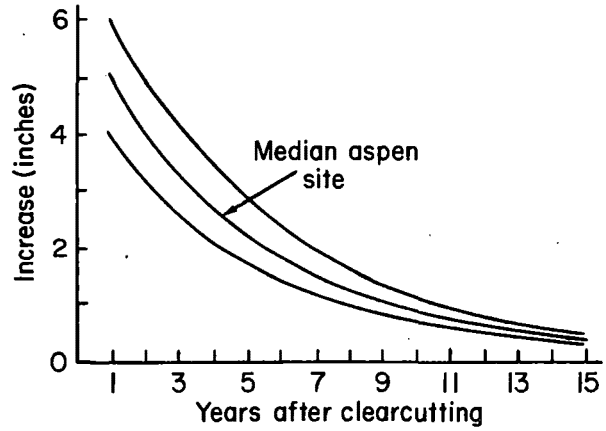


Figure 11.--Increase in water yield declines rapidly after clearcutting aspen, when regrowth is permitted (personal communication with Norbert V. DeByle, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Logan, Utah).

[18/] The Sheep Creek Water Evaluation Project by Max E. Robinson, Fishlake National Forest, Utah. Abridgement by Delpha M. Noble, 1973, USDA Forest Service, Intermountain Region, Ogden, Utah. 24 p., Mimeographed.

[19/] Personal communication with Ronald K. Tew, Soil and Water Management, USDA Forest Service, Intermountain Region, Ogden, Utah.

products is repeated every 80 years, for example, the long-term average increase in water yield for the 80-year period would be about one-third inch annually on the areas acutally treated. If clearcuts were kept small (5-15 acres) and the treament cycle reduced to 25 years, as might be done to enhance browse and forage production for big game animals and livestock (Patton and Jones 1977), the increase would average about 1 inch per year for the 25-year cycle.

As in the other forest types, the total water yield potential depends on the methods of treatment and the extent of application. If all 3.3 million acres of aspen were type converted at one time, the increase in water yield could reach 1 million acre-feet per year (assuming an average increase of 3-5 inches); almost all of it would be in the Upper Basin. However, the trade-offs would be great. Realistically, treatable acres would be much fewer, and acceptable treatment methods would be less water productive than those that produce the greatest increases.

## Southwestern Ponderosa Pine Forests

Ponderosa pine occupies some 7.5 million acres in the Colorado River Basin, more than any other timber type. The Lower Basin claims about 6 million acres, mostly in Arizona, and the Upper Basin about 1.5 million, mostly in the southern portions of Utah and Colorado. Approximately 6.9 million acres are considered suitable for commercial timber production (table 4), but of these, nearly two-thirds of a million acres are in National Parks, wilderness areas, high value scenic areas, and similar categories. About 70% of the ponderosa pine is on public lands; most of the rest is on Indian lands.

The elevation range for ponderosa pine is between 6,000 and 9,000 feet. Ponderosa pine grows on drier sites than mixed conifer and subalpine species, but requires more moisture than the pinyon-juniper type. Ponderosa pine occupies wetter sites than oak brush, although Gambel oak and chaparral species are common understory plants in the lower fringe area of the pine.

The climate where ponderosa pine grows is moisture deficient through much of the growing season. Average annual precipitation is about one-half snow and varies from 15 to 25 inches in the Upper Basin and 20 to 25 inches in the Lower Basin. Winter moisture is sufficient to wet the soil by winter's end and contribute to streamflow. A snowpack usually develops, but in the lower, warmer sites may be light. Spring weather is typically dry until summer rains begin usually by July in the Lower Basin. Summer moisture is much less prominent in the Upper Basin. Mean annual temperature ranges from about 44° F in the southern Rocky Mountains and Colorado Plateau to 52° F in the Basin and Range physiographic province (Schubert 1974). The overall average for the ponderosa pine type is about 47° F.

Water yield is derived mostly from snowmelt and averages about 3.5 inches annually, although the amount may vary from 2 to 6 inches depending on precipitation, elevation, latitude, and soils. Surface runoff (overland flow) is the main source of streamflow on tight volcanic-derived soils on Beaver Creek in central Arizona (H. E. Brown et al. 1974). Streamflows generated by surface runoff are flashy, and they quickly decline when rain or snowmelt ends. On permeable soils, rain and melting snow soak into the soil, where water moves much more slowly to the stream channels, and flows may be sustained for weeks or even months without precipitation. However, when water is delayed in its passage through the soil and rock, it is subject to greater losses to evapotranspiration and deep seepage than if it runs directly off the surface. This may help explain why water yields from volcanic-derived soils are considered to be greater (5.3 inches per year average on Beaver Creek experimental watersheds) than from sedimentary-derived soils under similar climatic regimes in Arizona (Baker and Brown 1974).

The potential for increasing water yield in the ponderosa pine type is less than in subalpine and mixed conifer forests, possibly because the pine forests are drier. Clearcutting produced the largest increases in streamflow obtained from treatments on the Beaver Creek experimental watersheds, where most of the watershed research in the ponderosa pine has been done. Water yield increased 33% on the average or 1.8 inches per year for 8 years after clearcutting trees from a 455-acre watershed in the 23-inch precipitation zone (Baker 1975, H. E. Brown et al. 1974). Before treatment, the pine and associated oak and juniper trees together measured 104 square feet basal area per acre. All residual slash was piled in windrows oriented to trap and shade snow. The second largest increase averaged 19% or 1.3 inches per year after removal of 75% (from 120 to 30 square feet per acre) of the timber basal area by thinning. Here, also, the residual slash was piled into windrows. Other strip cut treatments removed less cover and produced smaller (1.0 to 0.8 in.) water increases.

The treatments on Beaver Creek increased water yield primarily by decreasing water loss by transpiration. By reducing the soil moisture deficit, the surface soil reaches saturation sooner and more water from the melting snowpack runs off. In addition, slash windrows and cut strips trap snow and expedite its melt and delivery to the channels (Baker 1975). Where streamflow is primarily subsurface in origin, the results would be much the same except that orientation of windrows and cut strips up and down slopes would be less effective in moving water to the channels.

Water yield improvement studies in ponderosa pine outside of Beaver Creek are limited. However, one other watershed experiment in eastern Arizona should be included, even though the area may be considered transition between ponderosa pine and mixed conifer. The 900-acre West Fork of Castle Creek was harvested in 1965-67 as a

first step toward an even-aged management system (Rich 1972). The area is at 8,000 feet elevation and receives 25 inches of precipitation annually, almost one-half in the summer months June-September. Although ponderosa pine predominates, mixed conifer species occupy northeast exposures, which indicates that the site is at the upper fringes of the ponderosa pine type. Surface runoff is less pronounced than on Beaver Creek; however, streamflows are intermittent. One-sixth of the watershed was clearcut in patches fitted to stands of overmature and dwarf mistletoe-infected tree classes and areas. The remaining five-sixths of the area was selectively harvested to put the stand in the best growing condition possible by reducing the stand basal area from 135 to 63 square feet per acre. Streamflow from the watershed increased 29% on the average for 10 years, or an equivalent depth over the watershed of nearly 0.6 inch. These results closely parallel the experience at Beaver Creek.

Other investigators in the Rocky Mountains and Pacific Northwest report soil moisture responses and water yield increases in the ponderosa pine type similar to, or even greater than, occurred at Beaver Creek. Up to 3 inches more water was found in the soil (presumably available for streamflow) following thinning of ponderosa pine on plots in Oregon (Helvey 1975), Black Hills in South Dakota (Orr 1968), and central Washington (Herring 1970). Water yield increased an average of 3.5 inches the first year after wildfire swept through three ponderosa pine watersheds in central Washington (Helvey 1973), and water yield increased by about 2 inches after heavy logging on a large watershed in central Oregon (Berndt and Swank 1970).

While the potential increase in water yield may be as much as 2 to 3 inches by clearing ponderosa pine forests, it is doubtful that large areas will be permanently converted to grass. Several valuable resources besides water and timber must be recognized. These include forage, wildlife, soil esthetics, and recreation. If the response of these resources to treatment practices is known, management alternatives can be selected to get the best mix of products possible. Some preliminary models have been developed for this purpose for average ponderosa pine stands on volcanic soils in Arizona (H. E. Brown et al. 1974). These models have been depicted as single-function graphs (fig. 12) to show how resource output is affected by changes in basal area. If maximum herbage and water production were sought, basal area should be reduced to zero and kept there (fig. 12). However, maximum timber is produced when the growing stock level is near 60 square feet of basal area per acre (Schubert 1974), and deer will make most use of the area at about 40 square feet per acre, although squirrels require more trees than this (Patton 1977). Landscape esthetics are considered most pleasing at a higher stocking level.

Operating at a basal area of 60 square feet per acre in ponderosa pine may not necessarily produce the bext mix of resource outputs. Other alternatives are possible, the best mix being determined by the land manager in light of specific objectives and constraints.

The problem of estimating the potential for increasing water yield is further complicated by lack of complete inventory data on stand and stocking conditions in the pine type. Because ponderosa pine is a valuable timber tree and is relatively accessible, most of the original stands have been cut over, leaving much of the area in an understocked or poorly stocked condition. Some of the poorly stocked stands have been occupied by heavy oakbrush understory, further complicating management options. Schubert (1974) estimated that only 35% of the commercial ponderosa pine forests in the Southwest (Arizona, New Mexico, Colorado, and Utah) are 70% or more stocked. Nearly the same amount (36%) is stocked at 40% to 70%, and the rest (29%) is less than 40% stocked. Ironically, many individual stands within poorly stocked areas are overstocked. Schubert estimated that half of the forested area classed as 40% or more stocked probably contains overstocked stands. Dense stands of young growth have resulted from protection from fire, reduction in livestock grazing, and a 30-year wet period that started about 1905. Long-term silvicultural treatments would be required to restore timber productivity to overstocked and understocked stands. Some areas may already be producing water at a near maximum rate because of low stocking. Bringing these areas to a higher stocking level may cause water yields to decline. Thinning dense stands should increase yield if thinning removes half or more of the crown cover.

The following description (Senn 1976) of commercial ponderosa pine forests in the Salt-Verde Basin in Arizona illustrates the complexity of the pine type and the problems associated with estimating water yield potential. Management objectives and practices can vary considerably with ownership. In the Salt-Verde Basin, for example, commercial ponderosa pine forests occupy 1,610,000 acres, nearly one-fourth of all in the Colorado River Basin. Of these, 56% is under National Forest Administration, 37% Indian Trust, 5.5% state and private, and 1.5% other federal agencies. In the State of Arizona, 66% is National Forest and 29% Indian Trust.

Of the 897,750 acres of commercial forest land within National Forests in the Salt-Verde Basin, 12% are considered inoperable. Inoperable lands are defined as having logging constraints--either physical, land use, or administrative--including wilderness and similar areas. The remaining operable lands are further broken down into merchantable (48%), fringe pine (23%), dog-hair thickets (8%), and nonstocked (8%). Little opportunity exists to increase water yield on lands classed as inoperable, although future technology and economics may allow some of these areas to be treated.

The greatest opportunity for increasing water is in the mechantable stands and in the dog-hair thickets. The fringe pine is less certain, since it is found on drier, poor quality

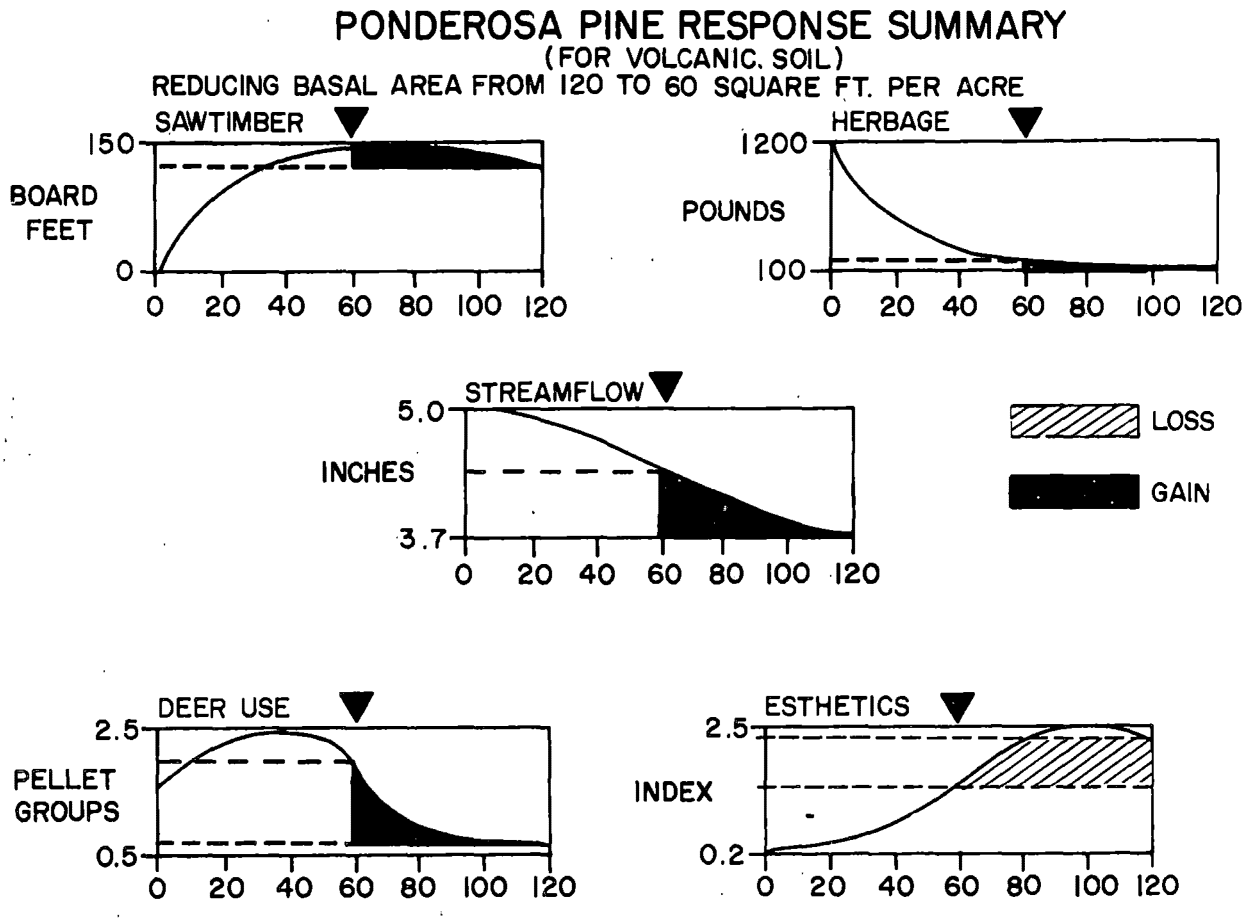


Figure 12.--Differences in resource outputs resulting from changes in timber basal area in ponderosa pine (Baker and Brown 1974).

sites, primarily as a transition zone between merchantable pine and the chaparral and pinyon-juniper types. Type conversion on some of the wetter sites possibly would increase water comparable to the chaparral potential. Nonstocked lands that are now covered by brush could be expected to produce more water for a time if the brush were controlled in reforestation activities. Eventually, the increased yields would decline to some intermediate level as the forest matures. Nonstocked stands that are now covered by herbaceous vegetation could be expected to yield less water if reforested.

Some objectives and possible future directions in ponderosa pine management are summarized here to illustrate the multiresource planning approach. The 67,613-acre Woods Planning Unit[20] on the Coconino National Forest in Arizona is considered to be representative of more than 40% of the ponderosa pine habitat in Arizona (Carder 1975), and, in a general way, may also be indicative of water yield potential in commercial pine forests in the rest of the Colorado River Basin.

Ponderosa pine covers approximately 80% of the Woods Planning Unit, most of which (48,612 acres) were considered suitable for treatment. Four management alternatives were considered in the environmental statement. They represent a wide variation in overall management emphasis as well as in commodity outputs, environmental impacts, and economic returns.

Alternative 1. Emphasis is placed on production of timber and wood products on a sustained yield for essentially all of the area. This alternative is similar to the current management direction. A maximum of 5% of the area (2,400 acres) would be allowed for other emphasis (e.g., wildlife or near natural).

Alternative 2. Overall emphasis is on production of timber and wood products and

[20] Final Environmental Statement, Land Use Plan Woods Planning Unit, Coconino National Forest, USDA Forest Service, Southwestern Region, Albuquerque, N. Mex. 232 p. January 1977.

on maintenance and improvement of wildlife habitat. Approximately 25% of the area would receive wildlife emphasis, and 10% would receive near natural emphasis.

Alternative 3. Near natural conditions and esthetics are emphasized, although commodity production is still retained on portions of the more productive soils. It could be considered as an Environmental Quality Plan. Approximately 58% of the area would be left in near natural condition.

Alternative 4. Water yield and forage production are emphasized, although timber production and wildlife habitat get considerable emphasis as well. It could be considered as meeting the objectives of a National Economic Development Plan because it would yield the greatest net present value of the considered alternatives. Approximately 25% of the area would receive wildlife emphasis, and 5% would be left in near natural condition.

Alternative 2 was the selected plan for the ponderosa pine area because it produces high commodity outputs and also significantly improves big game habitat. This alternative gives the second highest outputs of timber, forage, and water. It maximizes deer and elk habitat and is second only to the near natural emphasis (Alternative 3) for habitat of turkeys, squirrels, and birds. However, it assumes the greatest risk of large fires, but only slightly greater than Alternative 1. Water yield in Woods Canyon (a 10,700-acre experimental watershed entirely within the Woods Planning Unit used to evaluate water yield and sediment production) would be increased by approximately 0.7 inch, or 12% of the natural water yield which averages nearly 6 inches. Alternative 1 also would increase water yield by 12%, and Alternative 3 by 6%.

Alternative 4 would return the greatest yield of forage and water (16%) and has the greatest immediate economic return from commodity products. However, it also has the most severe environmental impacts and the lowest rating for turkeys, squirrels, and birds, and the second lowest for elk and deer.

Five management treatments--near natural, shelterwood, wildlife, irregular strip cut, and severe thin--were considered. Neither irregular strip cut nor severe thin were included in the selected alternative, although they were included in Alternative 4. The shelterwood system of timber harvesting would be used on 65% of the pine area in the selected alternative. Stocking levels would be maintained at 60 to 80 square feet basal area per acre, depending on soil type. Approximately 25% of the pine area would receive the wildlife treatment, which would create openings of 1 to 10 acres, comprising 10% to 20% of the area. The openings would be seeded to grasses and forbs; if pine naturally restocked the openings, new openings would be cut to maintain 10% to 20% in this category. The remaining portion of the wildlife treatment area would be managed similar to the shelterwood system, except that selected thickets of young trees would be left for cover at the rate of one 5- to 20-acre thicket per 100 acres of forest outside the openings. Some slash piles would be left. The remaining 10% of the pine area would be given near natural treatment under the selected alternative. This would be nonintensive management with emphasis on undeveloped area values and maintenance of natural appearance. Timber harvest would be restricted to salvage only; there would be no thinning or other timber management activities.

The projected water yield increase of 0.7 inch is based on reducing pine basal area from about 120 square feet per acre to between 60 and 80 square feet per acre under the shelterwood treatment system and from the openings created for wildlife. This projected increase is for the Woods Canyon watershed, and is significantly higher than for the entire planning unit, where the timber basal area is lower and nontreatable areas larger than on the experimental watershed (Carder 1975). The expected water yield increase is 0.5 inch over the entire planning unit. However, if alligator juniper, which comprises approximately 16% of the planning unit, is excluded, the increase would average about 0.6 inch per year for the total area in ponderosa pine.

The following summarizes water yield potential in southwestern ponderosa pine:

1. Water yield can be expected to increase on the average 1 to 3 inches from clearcutting ponderosa pine with basal area greater than 100 square feet per acre. Flow increases should continue after clearing for 10 or more years until young trees are established, and then should decline as the forest cover matures over the next few decades. Type conversion to grass should perpetuate the yield increases. If all 7.5 million acres of ponderosa pine within the Colorado River Basin were cleared of trees at one time, the potential for increasing water yield could reach 1 million acre-feet annually (based on an average increase of at least 1.6 in.). Eighty percent would be in the Lower Basin.
2. Present multiple use considerations preclude large-scale clearcutting and type conversion of these forests. Alternatives include individual and group selection harvest of trees, patch and irregular strip cuts, thinning, and combinations of these methods. From 0.1 to 1 inch of extra water may be expected, depending on the amount and method of forest reduction. The average increase is probably about one-half inch, unless emphasis is placed on water production. Under a water emphasis plan, almost 1 inch might be expected on the better sites where substantial reductions can be made in forest cover by patch or strip cuts or severe thinning to a stocking level of about 40 square feet basal area per acre.

3. Estimating the total water yield potenital under multiple use considerations is difficult because the amount and location of ponderosa pine lands suitable and available for treatment is not known. Low stocking levels (less than 40%) on about one-third of the commercial pine may preclude water increases from these areas regardless of management emphasis, except for clearcutting. Water yield could actually decline on some of these areas if stocking levels are brought up to timber management goals. On the remaining two-thirds (4.2 million acres), the potential is more promising, although on at least one-half of this area there may not be sufficient pine cover remaining to get significant water yield response without reducing the stand below optimum management levels for wood products and and other uses. This leaves about one-third (2.1 million acres) of the commercial ponderosa pine on which intensive management activities might be expected to increase water yield by 0.1 to 1 inch, or, on the average, about 96,000 acre-feet per year if applicable to the entire 2.1 million acres. About 80% would be in the Lower Basin. The amount might be further increased by emphasizing water production on favorable sites, and by type conversions in noncommercial and fringe stands.

Mountain Brush

Mountain brushlands in Colorado and Utah are composed largely of Gambel oak in brush form, growing in clumps or thickets 2 to 12 feet high (Brown 1958), although this species sometimes attains tree form and size on the better sites. Most investigators consider Gambel oak to be a climax type[21/] (Sweeney and Steinhoff 1976), most likely an edaphic or topographic climax. Associated shrubs, which sometimes may dominate the site, are chokecherry, serviceberry, snowberry, big sagebrush, mountainmahogany, and other woody species. Although sometimes classified as chaparral, the mountain brush type differs in that most of the species are deciduous; thus they are active only in summer. Mountainmahogany is a notable exception, capable of transpiring water whenever weather conditions permit. The type is found at elevations from 6,000 feet to as high as 9,000 feet on warm, dry exposures. Gambel oak often forms an understory in the ponderosa pine. In many areas, it replaces ponderosa pine that has been logged out or destroyed by fire.

Mountain brush is extensive only in the Upper Colorado Basin, where approximately 3.3 million acres have been delineated in the western Colorado and eastern Utah portions of the Basin (table 2). Less than a million acres are under National Forest administration, with perhaps as many more acres under Bureau of Land Management jurisdiction. However, ownership data are incomplete.

The climate is semiarid to subhumid. Mean annual temperature ranges from 39° to 50° F, and the average annual precipitation may range from 16 to more than 24 inches, much of it falling as snow. Water yield appears to be similar to the ponderosa pine type, and can be expected to average between 1 and 6 inches, depending on climate and site factors.

The potential for increasing water yield by treating mountain brush appears similar to that from the chaparral, if the brush is converted to a shallow-rooted cover such as grass. Based on plot studies in central Utah, Tew (1966) and Johnston et al. (1969) suggested that type conversion of oak brush could reduce evapotranspiration 5 to 6 inches during most years. However, Tew (1967b) reported only about 1 inch of potential water savings the first year after cutting mature Gambel oak and allowing sprouts to regenerate the stand. By the second year, the sprouts were using as much water as the mature oak brush. By the third year, the sprouts were using more water than the mature brush. In further plot studies, Tew (1969) found that when sprouts were controlled after cutting mature brush, and grass was planted, soil water depletions were less by 3.1 inches the first year and 2.4 inches the second year.

Without further watershed testing, the on-site potential for increasing water yield in the mountain brush type remains somewhat conjectural. Since response from treatment of oakbrush appears to be less than from chaparral, it is possible that the oakbrush also will respond less well than chaparral under large-scale management efforts. Therefore, assuming type conversion to grass or grass-forb cover with sprouting controlled, water yield increase for mountain brush is projected at 1 to 3 inches. If sprouts are not controlled, or if other deep-rooted species are allowed to invade, water savings will probably disappear within 3 to 5 years. Where oakbrush is controlled to regenerate ponderosa pine, water yield would be expected to remain higher for perhaps 10 to 20 years until the pine recovers the site, then decrease as the trees mature.

If all 3.3 million acres of mountain brush were converted to grass, theoretically, an additional 600,000 acre-feet of water per year would be possible. However, not enough information is available on the mountain brush type to refine this estimate, as was done in the chaparral. In-

21/ In the following report, Steinhoff describes oak brush associations in southwest Colorado as temporary climaxes which will remain relatively stable in vegetative composition for at least 500 years: "Management of Gambel oak associations for wildlife and livestock," 119 p. Report prepared by Harold W. Steinhoff, Colorado State University, under Intergovernmental personnel agreement with Rocky Mountain Region, USDA Forest Service, March 1978.

ventories are needed to determine how much of the 3.3 million acres could be managed for water and forage production, where these areas are located, who owns them, and how other resources would be affected. As with the chaparral, much of the mountain brush may be too dry (low density), too steep, or otherwise unsuitable for treatment.

Big Sagebrush

Big sagebrush is found on some 26 million acres in the Colorado River drainage. Mostly it grows in the Upper Basin where at least 18 million acres are classified as big sagebrush, comprising three species and two subspecies (Beetle 1960; Schlatterer 1973). Big sagebrush thrives across a broad range in climate, soil, and physiography. It is not restricted by elevation, as are many other plants, and is found as high as 10,000 feet in the mountains and high plateaus. Some species grow short, while the largest normally attain a height of 3 to 6 feet on good sites. Big sagebrush is well adapted to a warm, dry growing season where the shrubs use moisture stored in the soil from winter snow and rain. Most roots are located in the upper 2 feet of soil, although tap roots or dominant lateral roots may extend to 5 or 6 feet, or deeper if soils permit.

Grazing is the dominant use of most sagebrush lands. Sagebrush provides important habitat for wildlife, both game and nongame animals. The sage grouse, for example, is totally dependent on sagebrush, the antelope to a lesser extent. Both seem to prefer Wyoming big sagebrush, a dwarf shrub, to other sagebrush types. Mountain big sagebrush is a flat-topped shrub up to 3 feet tall that commonly grows above 7,000 feet. Mountain big sagebrush shows the most promise for water yield improvement (Sturges 1975).

The climate is semiarid to subhumid. Precipitation averages 8 to 20 inches in the big sagebursh type, where one-half to two-thirds falls in the winter, mostly as snow. The relocation of snow by winter winds and the resulting water loss by sublimation during transport are important hydrologic features. Snow accumulates through the winter but melts rapidly in the spring producing the bulk of the annual yield. Some of the melting snow may be exported from the melt site by overland flow, although most soaks into the ground where it is available for onsite use. In the higher precipitation areas, melt water enters local ground water systems and supports perennial streamflow. Sagebrush usually is considered low in production of water because of low precipitation. Water yield is less than 1 inch on most sagebrush lands, but where precipitation exceeds 14 inches, yield may reach 3 or 4 inches on the most favorable sites (Sturges 1975).

The potential for increasing water yield by type conversion of sagebrush is poor and limited to mountain big sagebrush, or types with similar growth forms, on lands above 7,000 feet elevation where precipitation is mostly snow and averages 15 inches or more per year (Sturges 1975). Areas meeting these criteria are restricted to portions of southwestern Wyoming, the Uinta Mountains, and the Colorado Rockies. None of the sagebrush in the Lower Basin has potential for increasing yield. Converting mountain big sagebrush to herbaceous vegetation would probably increase water yield no more than 15%, or one-half inch or less under very favorable conditions. No long-term watershed studies have been conducted in the mountain big sagebrush type. However, soil moisture studies (Sturges 1977) show that soil moisture savings decline with time and are negligible 10 to 15 years after treatment.

Brush removal will not affect water yield where soils are shallow and precipitation is not sufficient to rewet the soil profile each snowmelt season. As with other brushlands (Hill and Rice 1963), certain conditions are essential before type conversion can effectively increase water yield: (1) rooting depth of sagebrush should be deeper than 3 feet and must exceed rooting depth of replacement vegetation, (2) precipitation must exceed evapotranspiration by the replacement cover, and (3) the replacement cover must be kept relatively free of deep rooted plants. Response to conversion will depend on how well these conditions are satisfied. Even then, streamflow may not increase despite onsite savings in evapotranspiration, unless the areas to be treated normally produce some streamflow at least part of the year.

Sagebrush lands are mostly managed by the Bureau of Land Management and the Forest Service. In Wyoming, some 5% to 8% of the total sagebrush acreage has had brush control work, but a breakdown by species and subspecies is not available. Kearl (1965) indicated that about 75% of the sagebrush converted in Wyoming was located between 7,000 and 9,000 feet elevation, which suggests that brush control has been applied mainly to the mountain big sagebrush type. The increase in treated acreage since 1970 has been small; little public land has been treated by the Bureau of Land Management or the Forest Service in the 1970's because of environmental concerns. Since much of the treated land was converted 10 or more years ago, considerable retreatment would be necessary in the near future just to maintain treated land reasonably free of brush. Also, controlling sagebrush for water yield benefits alone may never be economically sound, although improvement of grazing values would help to pay for treatment costs.

Recent research in snow management suggests additional possibilities for increasing water yield on sagebrush lands. When cold winter winds sweep open country, a third or more of the blowing snow is subject to evaporation by sublimation at sub-freezing temperatures (Schmidt 1972; Tabler 1973). Some of this loss can be prevented by capturing blowing snow behind snow fences before it evaporates. Tabler (1975) developed a conceptual model for estimating the transport and evaporation of blowing snow, and

found that his estimates agree with measured snow accumulations in southeastern Wyoming. The approach has been used successfully for designing snow fence systems along highways (Tabler 1974). Snow fences can be applied to management for water yield purposes.

Fences 6 to 12 feet high specifically designed for the topography, vegetation, wind, and amount of snow expected at each site, are capable of trapping 80% of blowing snow in drifts containing 300 to 1,000 cubic feet water-equivalent snow per lineal foot of fence. By concentrating snow in large drifts, more of the melt water percolates to ground water and streamflow than when snow is more uniformly distributed. The trapped snow is snow that would otherwise evaporate, and thus is "new" water completely outside of the traditional resource base (Sturges 1975). This water can be utilized with little impact on other land uses, although the visual impact of snow fences must be taken into account.

Some assumptions are necessary to illustrate the potential for snow management on big sagebrush lands: (1) average winter precipitation is 8 inches or more in the form of snow, (2) roughly one-third of the snow evaporates under normal conditions, and (3) about one-half of the snow subject to evaporation can be trapped by snow fences. If these conditions prevail, about 1.3 inches more water would be present in the form of large drifts scattered over the landscape. Some of this water is subject to evaporation before it melts (Rechard 1973), leaving perhaps 1 inch of water to enter the soil or run off. The amount actually contributing to streamflow would depend on the soils, geology, and topography of the area. Streamflow may not increase unless a drainage system normally carries water at least part of the year.

Combining snow management with vegetation management probably offers the most promise to increase water yield on sagebrush lands (Tabler 1975). Snow entrapment could be made more efficient while improving the grazing resource at the same time, However, the economics of these practices have not been determined.

No projection of the overall potential for increasing water yield from the big sagebrush type is possible until reliable estimates are available of areas within the Upper Basin where brush control and snow management are feasible.

## Chaparral

The chaparral type is restricted almost entirely to the Lower Basin, where it covers about 3.5 million acres, mostly in Arizona. Unlike the mountain brush in Colorado and Utah, chaparral species tend to be low-growing shrubs with thick, evergreen leaves well adapted to heat and drought. Shrubs are deep rooted and reach best development on deep soils or on deeply weathered or broken rock mantles. Most species sprout prolifically from root crowns after fire or cutting, and produce few seedlings; however, the few that do not sprout produce abundant seed. Stands usually are mixed, with one species dominant. Shrub live oak is most abundant, followed by mountainmahogany. Other common shrubs are manzanita, Emory oak, silktassel, desert ceanothus, and sugar sumac. Where brush is dense, ground cover is virtually absent; where it is open, grasses and forbs may be abundant in the intershrub spaces. The type is found most commonly on rough, broken terrain from 3,000 to 6,000 elevation. The upper margin of the chaparral borders ponderosa pine or occasionally pinyon-juniper stands, while the lower margin borders semidesert grassland or southern desert shrub types.

The climate is semiarid but approaches subhumid at some of the higher, cooler sites. Precipitation averages about 21 inches overall, but ranges from as low as 16 inches at the lower fringes, to more than 25 inches at the wettest site. Half or more of the precipitation falls in the winter, mostly as rain, although some snow falls each year. Within the chaparral zone, mean annual temperatures range between 50° and 65° F. Dry weather prevails much of the year, particularly late spring to early summer, and again in the fall months. Evaporation from a Weather Bureau Class A pan averaged 74 inches per year at 5,100 feet elevation and 82 inches at 3,500 feet elevation where chaparral flourishes (Hibbert et al. 1974).

Water yield varies considerably in the chaparral depending on precipitation, climate, and soils. The overall average is about 1.2 inches, although the lower, drier sites produce very little. Except in dry years, winter rains recharge the regolith, which is the source of intermittent streamflow. Contrary to popular belief, surface runoff (overland flow) is not a common source of streamflow in the chaparral. Only after fires or other severe disturbance, does the soil fail to absorb all but the heaviest of rains. Then, for a few years, while soil wettability is impaired and protective cover is deficient, intense rainfall fails to infiltrate completely, and runoff and erosion can be severe (Glendening et al. 1961, Hibbert et al. 1974, Scholl 1975).

The potential for increasing water yield is good where shrubs are dense and precipitation averages more than about 20 inches per year. Where shrub crown cover is less than 30%, little or no increase in water can be expected from removing shrubs. Type conversions to grass on small experimental watersheds in central Arizona have increased streamflow on all watersheds tested. Increases averaged less than one-half inch per year where precipitation averaged about 18 inches, and from about 2 to almost 6 inches per year on watersheds where precipitation averaged 20 to 25 inches (Hibbert et al. 1974). Assuming an average precipitation of 22 inches for treatable chaparral, the expected onsite increase in water yield is about 3.8 inches (fig. 13).

The key to increasing water yield in the chaparral is the replacement of deep-rooted shrubs with shallow-rooted plants that use less water. Shrubs root to 20 feet or more (Davis and Pase 1977), and can deplete soil water much

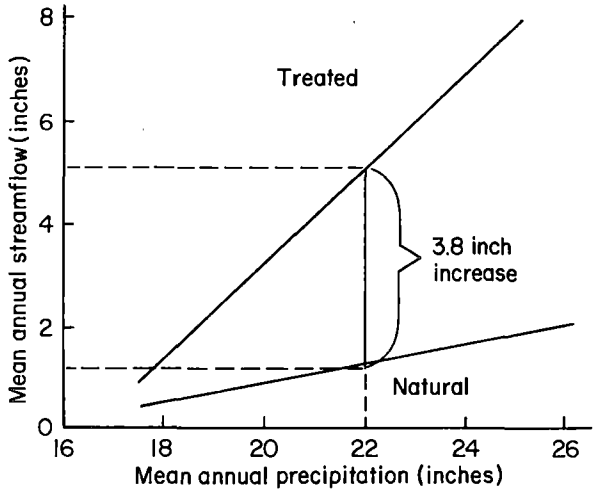


Figure 13.--Average water yield from natural and converted chaparral as a function of precipitation. Difference between lines is attributed to treatment (Hibbert et al. 1975).

more effectively than shallow-rooted grasses and forbs. Other factors probably contribute as well, such as less interception by grass and a greater tendency for seasonal dormancy by grass. However, it is believed that most of the water savings result from water being less available to the shallow-rooted plants. If the soil mantle remains partially charged as a result of these savings in evapotranspiration, seepage of excess winter recharge to groundwater and streamflow will start earlier, last longer, and be greater than if the shrubs were to remain in place. Experience with chaparral conversions bears this out: streams that once flowed a few months each year began to flow year-long after treatment. Furthermore, the higher level of water production continued as long as the converted areas were kept relatively free of shrubs.

Permanent shrub control is necessary to maintain increases in water yield. Most chaparral shrubs sprout vigorously from root crowns after fire or other control methods that simply topkill the plants. Without repeated control of sprouts, the shrubs quickly regain their former ability to use water, and within a few years the advantage in water savings is gone. Permanent control of shrub live oak, mountainmahogany, and other chaparral shrubs is difficult without herbicides, which offer an effective, though costly, method of eliminating the shrubs. Once the majority of the plants are eradicated, however, residual shrubs can be controlled by periodic prescribed burns (Pase and Knipe 1977), or by other means.

Some adjustment is necessary before extrapolating these research results to larger areas where conversion may not be as intensive, continuous, or as well maintained as on the experimental watersheds. If shrubs are left as buffer zones along the channel or between the channel and treated areas upslope, as would be the result where areas left for wildlife are interspersed with treated openings, some of the water saved upslope may be lost to intervening shrubs as it percolates downslope to the channel. Likewise, failure to reduce shrubs by 80% to 95%, as was done in the experimental watersheds, would give poorer results than obtained experimentally. Until predictive models of treatment response can be refined to include these variables, it is assumed that large-scale conversions will respond at about 80% of experimental results (Hibbert et al. 1974). Moreover, some of the increased flow will be lost to riparian vegetation downstream before it reaches storage reservoirs. However, since about 80% of the increase is produced in the dormant season when riparian vegetation is dormant, the proportion lost should be small, probably less than 20% of that reaching the headwater channels. Thus the average increase that can be expected downstream from chaparral under 22 inches of precipitation (considered average for treatable chaparral) is about 2.4 area inches or 0.2 acre-foot per acre actually converted to grass.

If all 3.5 million acres classified as chaparral could be converted to grass, the potential increase in water yield would be less than 700,000 acre-feet because much of the chaparral is too dry to respond well to treatment. Shrub crown cover of less than 30% is considered a poor risk for water yield improvement, although forage production might be increased. Some guidelines on treatable areas, economic feasibility, and water yield potential are available in a two-part "status of knowledge" report on the chaparral in Arizona. Part I covers water yield response and effects on other resources (Hibbert et al. 1974), and Part II analyzes economic feasibility of chaparral conversions (T. C. Brown et al. 1974).

The economic feasibility study looked at 850,000 acres of chaparral on Forest Service land in the Salt and Verde drainage basins above Phoenix in central Arizona. Chaparral was delineated according to cover density, land use, slope, and other criteria into 139 designated areas on which costs and benefits of conversion were evaluated. Of the 850,000 acres classified as chaparral, more than 500,000 acres were initially rejected because they were (1) in wilderness areas, (2) of less than 30% shrub cover, or (3) on slopes exceeding 60%. The remaining 333,000 acres, within the 139 delineated areas, were carefully examined for possible conversion. To allow for a pattern of chaparral and grass acceptable to wildlife and esthetic interests, no more than 60% of a delineated area was considered for treatment. This restriction further reduced the treatable area to 176,000 acres, about 21% of the total chaparral. Chaparral conversion was found to be economically feasible on only 96 of the 139 areas. Thus the area actually treatable was reduced to 147,000 acres, about 17% of the total chaparral within the Salt-Verde Basin.

By applying, without modification, the criteria developed in the Salt-Verde economic evaluation to the 3.5 million acres of chaparral in

the Lower Basin, the potential increase in water yield would be about 140,000 acre-feet per year. This estimate was based on the following assumptions.

1. More than one-half the chaparral acreage would be eliminated from consideration for treatment because of wilderness and similar classification, low shrub cover, and steep slopes.
2. Of the remaining chaparral, no more than 60% would be converted to allow for a brush and grass mosaic acceptable to wildlife and esthetic interests. This restriction would further reduce treatable acreage to about 700,000 acres, or 20% of the total area.
3. Adjustments for on-site and transmission losses would reduce the increase expected downstream to 2.4 inches or 0.2 acre-foot per year for each acre of chaparral actually converted to grass.

If more than 20% of the chaparral could be converted, a greater increase in water yield would be possible. However, unfavorable economics might restrict treatment to less than 20%. Also, management objectives and policy differ among land owners, which further complicates attempts at realistic estimates of the management potential.

Nearly one-half (48%) of the chaparral is on state, Bureau of Land Management, private, and Indian lands (table 3). Inventories are less complete on these lands, although it is known that fewer acres would be excluded because of wilderness classification. On the average, however, these lands tend to be drier, which lowers the potential for increasing water yield. Of the 1.8 million acres on National Forest lands more than 200,000 acres are in wilderness and other special use areas, where conversion is not compatible with present land use policy. A much larger portion, nearly 40% of the remaining chaparral, is considered too dry and open (crown cover less than 30%) to be a good risk for water yield improvement. Also, much of the chaparral is on excessively steep slopes for conversion. In the Salt-Verde evaluation, about 10% of otherwise treatable chaparral was on slopes steeper than 60%, which was the upper limit considered safe for conversion. However, some land managers feel that the 60% slope criterion is too steep for practical field application, and that the upper limit should be 50%, or even 40%. Since approximately 40% of the chaparral is on slopes between 40% and 60%, the steepness at which conversion can be safely accomplished is extremely important. Approximately 20% less area would be available for conversion if the maximum operable slope is lowered from 60% to 50%, and another 20% would be lost between 50% and 40% slope. Also, substantial acreages may be excluded for treatment, or given low priority, because of operational restrictions or geographic location, such as chaparral on slopes of isolated mountain ranges.

In view of the foregoing constraints and uncertainties, both the 1-acre-in-5 estimate for treatable chaparral and the 2.4-inch water yield increase projection probably should be considered the most optimistic potentials attainable by large-scale management efforts in the chaparral.

Use of the arithmetic average to describe annual water yield potential can be misleading because this value (2.4 inches in this case) will not be equalled or exceeded 50% of the years as would occur if precipitation and runoff were normally distributed. In the chaparral of central Arizona, precipitation is less than average about 58% of the years. Since runoff increases exponentially with precipitation, yearly runoff amounts are skewed even farther to the dry side of the distribution curve. Wet years tend to yield many times as much water as dry ones. Thus, even through precipitation exceeds the mean in only about 4 years in 10, more than 80% of the water yield increases are produced in these wetter than average years. Storage facilities are imperative to get full benefit of increased water yields in wet years. To the extent that downstream storage capacity is exceeded (which happened seven times in the past 50 years in the Salt-Verde Basin above Phoenix) and water is spilled, runoff increases from conversion would be lost to the full extent of the release, unless beneficial use could be made of the water downstream.

## Pinyon-Juniper and Woodlands

The pinyon-juniper ecosystem is the most extensive forest type in the Colorado River Basin. These dwarf conifers cover some 12.5 million acres in the Upper Basin and 20 million acres in the Lower Basin, together accounting for more than one-half of all the pinyon-juniper in the western United States. The type is most commonly encountered in the foothills, low mountains, and low plateaus between 4,000 and 7,500 feet elevation. Several recent symposia and state-of-the-art papers have focused on the pinyon-juniper ecosystem (Clary et al. 1974, Utah State University, 1975, Springfield 1976, Aldon and Loring 1977).

Common usage has established the name pinyon-juniper for this type, although junipers are usually more numerous. Typically a single species will dominate, and will sometimes form a pure stand. Common juniper species include Utah, Rocky Mountain, one-seed, and alligator junipers. Of the several pinyon pines, Colorado pinyon is the most well known and widespread, followed in importance by singleleaf pinyon. Associated shrubs and trees include bitterbrush, big sagebrush, mountainmahogany, cliffrose, ceanothus, and Emory and Gambel oaks. Several grasses and forbs are also found in association with the trees and shrubs, although soil is often bare in intervening spaces. A relatively high erosion rate is often attributed to the pinyon-juniper type.

Pinyon-juniper lands are mostly under federal administration: roughly 32% Bureau of Land Management; 20% Forest Service, mostly in the Lower Basin; 19% Indian Trust; and 29% other, including state and private holdings.

Though normally considered low in commercial value, the pinyon-juniper complex has many uses. Hurst (1976) views it as an important factor in the settlement and development of the West. Grazing and fire control have played major roles in the development of the stands as we know them today. Prior to settlement, pinyon-juniper stands were more open than today and confined mainly to rocky ridges and shallow soils. Heavy, year-long grazing reduced grass competition and curtailed the spread of fire, which normally retards spread of the trees. As a result, pinyon-juniper is more extensive today, and in many cases, denser than it once was. Despite a general decline in range productivity (Springfield 1976), these lands still are important producers of forage for livestock, food and cover for wildlife, and various woodland products such as fence posts, firewood, pinyon nuts, and Christmas trees.

The climate is semiarid. Mean annual temperature varies from 40° F to more than 65° F, and precipitation averages 12 to 18 inches, with local areas receiving up to 20 inches. Summer rains account for at least half of the precipitation in the Lower Basin, while winter rains and snow provide the bulk of moisture in the Upper Basin. Water yield on pinyon-juniper lands derives mostly from surface runoff and generally averages less than 1 inch on most areas (Dortignac 1960), although some of the better watered areas may approach 3 inches (Clary et al. 1974).

The potential for increasing water yield is poor. Under most conditions there is little or no response in water yield from removing or controlling pinyon-juniper (Clary et al. 1974, Gifford 1973, Myrick 1971, Collings and Myrick 1966, Dortignac 1960). Only when junipers were controlled by herbicides--no soil disturbance--did streamflow significantly increase (0.45 inch) on the Beaver Creek Experimental Watersheds in Arizona (Clary et al. 1974). Presumably, low precipitation, shallow soils, and a small difference in rooting depth between the trees and replacement cover combine to preclude significant water yield improvement from canopy reduction. Water that would normally go to the trees is fully utilized by the grasses and forbs after conversion (Skau 1964).

Pinyon-juniper conversion remains controversial (Lanner 1977). The primary objective of pinyon-juniper control work is to increase forage production, but watershed stability usually is an objective also (Hurst 1976). Wildlife habitat can be improved if openings are kept small and the "edge" effect large. Eradicating trees over large expanses is detrimental to many wildlife species, although too many trees also can be detrimental. Much of the control work is uneconomical (Hurst 1976, Clary et al. 1974), and the future of large-scale operations is uncertain. However, since water yield is little affected, there will be little impact on the water supply with or without treatment.

Other woodlands types are found in the southeastern portion of the Lower Basin. Brown and Lowe (1974) describe two classes: madrean evergreen woodlands (essentially oak woodlands), and riparian deciduous woodlands (including mesquite bosque and saltcedar communities). The latter types, being riparian, are considered in the section on upstream riparian vegetation. The oak woodlands are typically open with grass ground cover. Prominent oaks are Mexican blue, Emory, silverleaf, and Arizona oak. Apache and Chihuahua pine and Mexican pinyon are also present in some of the stands in southeastern Arizona. Acreage of the oak woodlands is not known. Significant growth is confined to the flanks of isolated mountain ranges in southeastern Arizona.

Precipitation in the oak woodlands averages 15 to 25 inches, one-half to two-thirds of it falling in the summer months. Water yield is low from these woodlands, not only because precipitation is low, but because much of it comes in the summer when the potential for evapotranspiration is high. Winter rains seldom are sufficient to recharge the soil profile, without which streamflow cannot be sustained beyond the occasional ephemeral flows from intense thunderstorms.

The potential for increasing water yield in the oak woodlands is considered poor. Except where trees have access to ground water, little water would be saved by removing the tree overstory because, during the hot weather, rainfall is absorbed by the soil and the portion that does not evaporate is returned to the atmosphere about as readily by one type of vegetation as another. Unless recharge occurs beyond the rooting depth of the grasses, there is little opportunity to increase seepage to groundwater and streamflow. Where subsurface water acquifers are tapped by roots of the woodland vegetation, water savings potential may approach those of the upstream riparian vegetation.

## Upstream Riparian

Riparian zones along streams and rivers in the Colorado River Basin are divided into upstream and downstream categories for purposes of this study. The downstream riparian zones are mostly phreatophyte-covered floodplains along the main stem of the Colorado River and similar areas along major tributaries. The U. S. Senate Select Committee (1960) reported 667,000 acres of phreatophytes and estimated use of water by these plants at 1.23 million acre-feet along the major streams in the Lower Colorado River Basin. Horton (1974) suggests 300,000 acres are present in Arizona alone along the lower main stem of the Colorado and the Gila Rivers. Horton further indicated that only about one-third of the 300,000 acres of phreatophytes would be treatable for water savings estimated at 130,000 acre-feet per year.

Somewhat larger acreages of phreatophytes were proposed for eradication by the Lower Colorado Region Comprehensive Framework Study (PSIAC 1971b). By these projections, eradication of phreatophytes on 141,000 acres along the lower main stem would save 404,000 acre-feet of water per year, eradication of 100,000 acres along the Gila River would save 200,000 acre-feet, and eradication of 20,000 acres along the Little Colorado River would save 20,000 acre-feet. These estimates of water savings total 624,000 acre-feet from 261,000 acres of phreatophytes in the Lower Basin. No estimates of phreatophytes or water savings were given for the Upper Basin. These water yield data are not included in the final assessment of this paper because phreatophytes along downstream reaches of the Colorado River and its major tributaries were outside the scope of this study. Horton (1976) and Horton and Campbell (1974) describe these downstream phreatophyte and riparian zones in detail, and discuss their multiple use values. Additional information is available from recent regional (Johnson and Jones 1977) and national (Johnson and McCormick 1978) symposia on the protection and management of riparian systems.

Upstream riparian zones consist of riparian vegetation along relatively small streams that drain to the Colorado River and its major tributaries. These riparian zones are of interest in this study because they are (1) areas of heavy water consumption, (2) conveyance systems for water yield increases generated on upstream watersheds, (3) areas having high potential for saving water by eradication of trees and shrubs, and (4) areas of high scenic value and high value for wildlife and recreation.

Of particular interest are streams that emerge from the mountains and flow across hot, dry lowlands to reach major streams and reservoirs. Consumptive use of water by riparian vegetation under what might be described as "oasis" conditions can be high, and accounts for the intermittent nature of many of these streams in their lower reaches. Total area occupied by riparian vegetation along these streams is unknown, since no acreages are available for the Upper Basin. Total area in the Lower Basin exceeds 100,000 acres (table 3). About one-half of these are on National Forest lands in the Gila Subbasin, mostly along streams emerging from the mountains in central Arizona south of the Mogollon Rim.

The most common riparian trees and shrubs at lower elevations are cottonwood, willows, saltcedar, arrowweed, saltbushes in saline areas, and mesquite bosques on the higher ground where the water table is deeper than next to the channels. At intermediate elevations sycamore becomes prominent, and at higher elevations cool-site species such as alder dominate the sites. Campbell and Green (1968) provide a detailed description of vegetation along Sycamore Creek, tributary to the Verde River near Phoenix.

Estimates of evapotranspiration from these upstream riparian zones vary considerably, depending on elevation, depth and permanence of water within the alluvium, and type and density of vegetation. Anderson (1976) estimated evapotranspiration losses from floodplain areas on 32 reaches of streams emerging from the mountains in central Arizona. About one-half of the streams were perennial; the remainder were intermittent or partly intermittent. Width of floodplains varied from 20 feet to more than 1 mile. Length of stream reaches totaled 1,287 miles, and floodplain areas totaled 42,000 acres, including bare soil but not water surface or bare rock. Alluvium depth varied from very shallow to more than 100 feet. Elevations ranged from 1,000 feet to over 7,500 feet. Anderson estimated that evapotranspiration on most of the reaches ranged from about 1.6 to 3 feet, and that potential evapotranspiration ranged from 4 to 6 feet.

The potential for water savings by management of riparian vegetation is greater than for most forest vegetation types because of the availability of water to the plants. Estimates of the potential vary, however, and actual measurements of water savings by treatment in upstream riparian zones are few. Three studies are briefly described here; two are in Arizona and one in southern California.

Rich et al. (1961) described the removal in August 1953 of alders and maples in the narrow riparian zone along North Fork of Workman Creek at 6,800 to 7,000 feet elevation in central Arizona. The total basal area of trees removed was 271 square feet, only 0.6% of the total basal area of all trees on the 248-acre watershed. No changes were detected in daily fluctuations or in annual or growing season streamflow volumes after the treatment. Actually, little was proved by this experiment, since the expected increase from removing such a small portion of the vegetation on the watershed was much too small to be detected at the streamflow gage.

Bowie and Kam (1968) reported a pilot study on a 1.5-mile reach of Cottonwood Wash in northwestern Arizona at an elevation of 4,000 to 4,300 feet. Treatments were applied in 1960 and again in 1961 to defoliate, and then eradicate, the riparian vegetation, mostly cottonwoods and willows, on 22 acres of narrow floodplain, which averaged about 120 feet wide. The riparian vegetation was not dense; actual canopy coverage of woody species was only 27%. Ground water was close to the surface, generally less than 2 feet.

Defoliation caused only small and short-lived reductions in water use by the riparian vegetation. Eradication, in contrast, reduced water consumption on the 22 acres from an average of 80 acre-feet (3.6-foot depth) per growing season to 42 acre-feet (1.9-foot depth) for a savings of 38 acre-feet (1.7-foot depth) per growing season for 3 years.

Woodland-riparian vegetation along 1.3 miles of Monroe Canyon in the San Gabriel Mountains in southern California was cut and regrowth was prevented to determine how much water could be saved by eliminating transpiration in these types of vegetation (Rowe 1963). The study reach was between 2,000 and 2,500 feet elevation, and

evapotranspiration was estimated at about 4 to 5 feet of water annually. Only about 10% (3.8 acres) of the cleared area supported true riparian growth (alder, maple, laurel, willow, sycamore, and associated shrub and herbaceous growth). Most of the cleared area supported a mixed oak-woodland type dominated by several live oaks and other tree species. The cleared area was 100 to 400 feet wide and extended up the steep sideslopes to an average height of about 50 feet above the stream.

The first cut in February-May 1958 was on 15 acres along the lower reaches of the main stream channel. Streamflow responded quickly, and from May through December (the drying season) flow increased by 17.4 acre-feet, or 1.2 acre-feet per acre treated. From January through April 1959 (the rainy season), the increase in flow amounted to 12.8 acre-feet or 0.9 acre-foot per acre treated, based on 15 acres. Actually, during this time the remaining 12 acres of canyon bottom were cleared, but Rowe attributed the increase in flow largely to the original 15 acres. Assuming this to be so, the increase in flow in the first 12 months amounted to 2.1 acre-feet per acre treated.

From May through December 1959 (the second drying season), with 38 acres cleared, flow increased only 0.4 acre-foot per acre treated. Rowe suggests that this low response might be attributed to lower than average rainfall during the previous rainy season, whereas rainfall in the winter prior to the first drying season was much above average. Despite the possible effects of wet and dry weather, substantial water savings were obtained by eradicating vegetation in the woodland and riparian zones in Monroe Canyon. By prorating the increases for the acreages treated over 2 years, the increase in flow averaged more than 1.2 acre feet per acre per year.

More pilot testing would be required before reliable predictions could be made of the potential for saving water by management of riparian vegetation in these small tributary streams. Horton and Campbell (1974) suggest that water savings of 1 to 2 acre-feet per acre treated is as close an approximation as is justified with the limited data available. This is probably true, but it seems appropriate to go one step farther and suggest situations where these water savings may or may not be attainable.

Transpiration by riparian vegetation depends largely on availability of water throughout the growing season. Persistence of shallow water along perennial streams, and many intermittent ones, favors development of dense riparian vegetation capable of transpiring large amounts of water. Obviously, not all transpiration can be stopped short of denuding the ground surface, and evaporation usually increases to partially compensate for reductions made in transpiration.

Knowledge of evapotranspiration rates in upstream riparian zones provides a basis for estimating potential savings. Anderson (1976) estimated evapotranspiration by riparian vegetation along many of the tributary streams in Arizona to be less than 3 feet per year. Thomsen and Schumann (1968) estimated evapotranspiration at 1.1 feet on a 10-mile reach (1,400 acres) of Sycamore Creek above its confluence with the Verde River near Phoenix. Their estimate for Tonto Creek above Roosevelt Lake is 2.6 feet (Schumann and Thomsen 1972).

It might be inferred from these evapotranspiration estimates that many of the riparian areas along these streams are not losing water at particularly high rates, and that treatment of these areas would produce relatively moderate increases in streamflow, perhaps one-half of the pretreatment evapotranspiration rate. Therefore, savings in the order of 0.5 to 1.5 acre-feet per acre per year may be realistic estimates for riparian zones where evapotranspiration is less than 3 feet per year, and savings up to 2 feet and even more might be possible where evapotranspiration is greater than 3 feet per year. Response to thinning or selective cutting of the vegetation is unknown. It is not known if heavy thinning would be required to effect water use reductions, or if water use would decline more or less linearly with uniform removal of trees, as might be expected where vegetation has an unrestricted water supply (fig. 6).

Another important feature of these tributary streams is that they act as conveyance systems for water yield increases generated on upstream treatment areas. Concern over the fate of this water prompted the Arizona Water Commission and the U. S. Geological Survey to conduct a study (Anderson 1976) to determine present, near-future, long-term future, and potential evapotranspiration losses from riparian zones along these streams. Thirty-two stream reaches totaling 1,287 miles were investigated to determine the possible increase in transitory water losses resulting from increases in flow at the upstream end of the reaches. The near-future and long-term future increases in evapotranspiration were considered to be negligible for perennial streams, which accounted for about one-half of the streams and about two-thirds of the total length.

Near-future evapotranspiration was considered to increase in intermittent reaches as a result of the water table being closer to the ground surface caused by greater input to the reach. Long-term future evapotranspiration would increase further, because of an increase in riparian vegetation density, as water became permanently available in areas that were previously intermittent. Estimates of evapotranspiration losses varied from one reach to another, butlong-term future losses usually more than doubled present losses.

Tonto Creek above Lake Roosevelt may be taken as an example. Length of reach was determined to be 59 miles and riparian area 4,907 acres. Estimates of present, near-future, and long-term future evapotranspiration losses in acre-feet per year were 8,700, 12,000, and 18,000, respectively. It was anticipated that if water yields were increased in Tonto Creek, up to 9,300 acre-feet (difference between present

and long-term future use) of the increase would eventually be lost to greater use along the stream by riparian vegetation, unless some remedial controls were applied to the vegetation.

One should not assume from these projections that the first 9,300 acre-feet of water yield increase produced on the watershed, or even the first 3,300 acre-feet (Anderson's near-future losses), would be consumed enroute to Lake Roosevelt. Evapotranspiration losses occur largely in summer, not in the dormant winter season when about 80% of the increase in water yield is produced (Hibbert et al. 1974). Since most of these intermittent streams flow in winter (except for very dry years), any increase in flow will simply add to the existing flow, and little additional loss should occur enroute to storage downstream.

In summer, if streamflow dries because of riparian vegetation, extra flow will likely be consumed also. If water yield increases are sufficient to create perennial flow in once intermittent streams, further depletion of summer flows will eventually reach a maximum rate (Anderson's long-term future losses), after which losses should remain constant. In the interim, however, transitory losses should be no greater than about 20% of the water yield increases unless the stream normally does not flow at least part of each year. In this event, the increases might entirely dissipate in the dry channel and bank alluvium.

Whether riparian vegetation is managed to increase the water supply or to assure undiminished conveyance of increases generated upstream, the implications are much the same. Clearcutting riparian vegetation destroys one of the most productive wildlife habitats known to exist in the Southwest. Furthermore, loss of shade to the stream channel and banks causes the temperature of small streams to increase, thus modifying the habitat for aquatic organisms. If the riparian vegetation is allowed to regrow, these detrimental effects may only be temporary, but so would be the benefits of water savings. If riparian trees and shrubs were permanently converted to grass, which mighdequately protect against erosion, the benefits of the riparian tree habitat would be permanently lost.

Aside from wildlife aspects, the riparian zone is valuable for recreation. The few permanent streams in the Southwest that are accessible are heavily used. They can be classified as a scarce resource, and as such will receive special consideration in management. It seems probably that restrictions will be placed on the amount and nature of vegetation removal in riparian zones (Campbell 1970). This does not mean that future management of these areas will not include some form of vegetation management. The recreation potential in some areas might be enhanced by thinning and partially removing trees and brush. Flood damage can be reduced by thinning or removing trees from channels and floodplains to prevent buildup of debris dams. Areas do exist where excessive riparian vegetation can be thinned and intensively managed for water yield improvement, although the opportunity is not as great as was once thought possible (Barr 1956).

In summary, removal of upstream riparian vegetation can produce greater water savings per unit area than any forest or brushland type. Water savings of from 6 to 24 area inches annually appear possible by eradicating riparian vegetation along permanently flowing streams. However, extensive removal of trees and shrubs from these areas could impair scenic and recreation values, adversely affect channel stability, and destroy productive wildlife habitat. Less than complete removal of trees and shrubs would correspondingly reduce the water savings potential. Therefore, it appears unlikely that upstream riparian areas can be counted on for significant augmentation of the water supply.

## Previous Estimates of Potential Water Yield Increases

### U.S. Senate Select Committee Estimates for Western U.S. 1960

The U.S. Senate Select Committee on National Water Resources (1960) made the first comprehensive determination of the potential for increasing water yield by vegetation management in the western United States. The committee found conditions favorable for improving water yield on about 15% of the area in the 17 western states (table 11).

From these data it is possible to calculate yield increases that total 12 million acre-feet,[22/] even more, if phreatophytes and Pacific Slope vegetation types are included. However, the report cautions against applications of this kind without carefully considering constraints and limitations that in practice could materially reduce these estimates. The report cites lodgepole pine

[22/] "Watershed Management--Water Supply Augmentation by Watershed Management in Wildland Areas" by William E. Sopper for the National Water Commission, Rep. NWC-EES-72-028. 149 p.

Table 11.--Potential increases in water yield for several vegetation types in 17 western states (U.S. Senate Select Committee on National Water Resources, 1960)

| Vegetation type | Area (thousand acres) | Potential[1/] increase (inches) | Percent treatable (%) |
|---|---|---|---|
| Commercial forests [2/] | | | |
| Lodgepole pine | 14,470 | 3.0 | 70 |
| Engelmann spruce-fir | 7,400 | 3.0 | 70 |
| White pine-larch-fir | 6,900 | 4.5 | 65 |
| Mixed conifers | 8,470 | 4.5 | 65 |
| True fir | 6,150 | 6.0 | 60 |
| Aspen | 4,000 | 3.0 | 70 |
| Interior ponderosa pine | 34,200 | 0.5 | 65 |
| Interior Douglas-fir | 9,000 | 1.0 | 70 |
| Pacific Douglas-fir, hemlock, redwood | 25,570 | - [3/] | - [3/] |
| Chaparral and Woodland | | | |
| Southern Calif. chaparral | 7,500 | 1.0 | 50 |
| Calif. woodland-grass | 9,000 | 1.0 | |
| Arizona chaparral | 5,500 | 0.5 | |
| Pinyon-juniper | 61,400 | 0.25 | 10 |
| Phreatophytes | 16,000 | - [4/] | - [4/] |
| Alpine | 10,000 | - [5/] | - |

[1/] Initial increase on area treated only. The reader is cautioned to be aware of application requirements and limitations before attempting to calculate volume of increases.

[2/] Commercial forest land: (a) capable of producing wood products, (b) economically available now or prospectively, (c) not withdrawn from timber production.

[3/] Opportunities for improving water yield are abundant.

[4/] Phreatophytes used an estimated 25 million acre-feet, of which 25% could be salvaged.

[5/] No increases in yield expected but better seasonal yield.

and spruce-fir types as examples of how water yield increases might be spread over the acreage of a vegetation type. When constraints and limitations were considered, the potential increases for these forest types were dramatically reduced.

Forests in the snowpack zone were considered the best opportunities for improving water yield by vegetation management (first six commercial forest types listed in table 11). Interior ponderosa pine, an important forest type in the lower Colorado River Basin, was estimated at 0.5 inch increase by thinning in dense young stands and individual tree and group selection cutting in sawtimber stands. Type conversion of chaparral in California was estimated at 1 inch increase, and in Arizona at 0.5 inch increase. Only about 30% of the chaparral and 69% of the woodlands (for 50% overall in table 11) were considered treatable. The pinyon-juniper type was considered 10% treatable at 0.25 inch potential increase. Phreatophytes and other riparian vegetation on 16 million acres were assumed to use 25 million acre-feet of water annually, of which 25%, or about 6 million acre-feet, was thought salvable. No increases were anticipated from the alpine zone, although concentration of snow by artificial barriers was expected to improve seasonal yield.

Other Estimates for Western U.S. 1966-1971

Storey and Reigner (1966) estimated the potential for increasing water yield in the Rocky Mountain and Southwest regions as part of a nation-wide evaluation in the mid 1960's. They projected water yield increases for the Rocky Mountain area at nearly one billion gallons per day (1,120,000 acre-feet per year) from about 42 million acres, roughly two-thirds of the total forest land available. The increase in water, which, overall, would average 0.33 inch, was not considered to be at the expense of timber production; if timber values could be foregone, much larger increases were considered possible.

In the Southwest, including Arizona, New Mexico, and California, Storey and Reigner (1966) considered eradication of phreatophytes to be the major source of water savings--as much as 5.6 million acre-feet per year. Conversion of chaparral and pinyon-juniper vegetation to grass would yield an additional 725,000 acre-feet per year. Of this amount, 55,000 acre-feet (0.5 inch) could be expected from treatment of 1.3 million acres of chaparral in Arizona. Most of the water yield increase attributed to Douglas-fir and ponderosa pine was in California; only 9,000 acre-feet per year was estimated for Arizona, and 17,000 for New Mexico. The reason for these seemingly low estimates from ponderosa pine and Douglas-fir in Arizona and New Mexico was not explained.

By summing their regional estimates, nearly 8 million acre-feet of potential increase is indicated for the Rocky Mountain and Southwest regions combined. However, phreatophyte eradication accounted for most of the increase. Without phreatophytes, the increase in the Southwest was slightly more than a million acre-feet, mostly attributed to California.

More recently, these national estimates were updated and better documented by Reigner (1970), Reigner et al.[23/] and Storey and Reigner (1971). The estimates pertaining to the western United States are summarized in table 12. Estimates of potential increases were developed from small watershed research data, pilot watershed studies, and forest surveys.[24/] Cost estimates (presumably prices of the late 1960's) also were included.

The southern Rocky Mountains area (Colorado, Utah, Nevada, Arizona, and New Mexico) was considered by the investigators to have the greatest potential for increasing water yield. This area is of greatest interest with respect to this study, since it largely encompasses the Colorado River Basin. Of the 2.02 million acre-feet of potential increase estimated for the southern Rocky Mountains area, 530,000 acre-feet were attributed to management of commercial forest lands. The low average cost estimate of $1.07 per acre-foot for this water, suggests that only a small additional expense over normal timber harvesting operations was considered necessary to get the extra water.

The analysis included estimates on some 6 million acres of chaparral in the southern Rocky Mountains area. It is not clear if some or all of the mountain brush in Colorado and Utah was included in this total. One out of every four acres was considered treatable by conversion to grass for an increase of 290,000 acre-feet, or 2.3 inches over areas treated. The investigators felt that these estimates of yield increase were conservative, based on averages--not extremes--of research results. Furthermore, they felt the increases could be sustained from year to year without serious impact on other forest resources, and without degrading water quality, or the forest environment.

The most obvious difference between the 1966 estimates of potential increase by Storey and Reigner and the updated 1969-71 estimates (table 12) was the 84% reduction from 5.6 to 0.9 million acre-feet of water salvage from phreatophytes in the Southwest. Mounting opposition to eradication of these dense stands of trees and brush from wildlife enthusiasts and conservationists was the major reason for the estimates to be scaled down. On the plus side, the updated estimates were about 890,000 acre-feet greater for commercial forests and about 90,000

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[23/] Irvin C. Reigner, Ralph C. Maloney, and E. G. Dunford. 1969. Unpublished report. USDA Forest Service, Washington, D.C.

[24/] The USDA Forest Service had just completed a reconnaissance level hydrologic survey on 42 million acres of National Forest lands in the Southwest. The results of the survey, known as the Pacific Southwest Hydrologic Analysis, were available to these investigators.

Table 12.--Potential increases in water yield and costs for several vegetation types in four western regions. (Unpublished data by Irvin C. Reigner, Ralph C. Maloney, and E. G. Dunford, 1969 report on file, USDA Forest Service, Washington, D.C.

| Region and vegetation type | Area (thousand acres) | Percent treatable | Potential increase (thousand acre-feet) | Cost (dollars per acre-foot) |
|---|---|---|---|---|
| Pacific Northwest (eastside portions of Oregon & Wash.) | | | | |
| Commercial forest | 23,000 | 61 | 160 | 3.17 |
| California (excluding north coastal area) | | | | |
| Commercial forest | 16,000 | 70 | 130 | 2.13 |
| Phreatophytes | 3,000 | 5 | 10 | 10.50 |
| Chaparral | 8,000 | 30 | 410 | 20.45 |
| Woodland-grass | 9,000 | 50 | 370 | 45.00 |
| | 36,000 | 51 | 920 | 27.62 |
| Northern Rocky Mts. | | | | |
| Commercial forest | 38,000 | 68 | 1,000 | 0.89 |
| Other | 3,000 | 30 | 40 | 90.00 |
| | 41,000 | 65 | 1,040 | 4.32 |
| Southern Rocky Mts. | | | | |
| Commercial forest | 26,000 | 58 | 530 | 1.07 |
| Phreatophytes | 16,000 | 15 | 900 | 14.00 |
| Chaparral | 6,000 | 25 | 290 | 18.00 |
| Other | 75,000 | 14 | 300 | 128.00 |
| | 123,000 | 24 | 2,020 | 28.11 |

acre-feet greater for chaparral than 1966 estimates. It is not known if these updated estimates were based on larger acreages of treatable area or on increased estimates of the onsite potential.

Pacific Southwest Hydrologic Analysis Estimates for National Forest System Lands in Colorado River Basin 1968

The objectives of the Pacific Southwest Hydrologic Analysis[25] was to make a first approximation of the potenital for improving water yield and for reducing sediment yield from National Forest System lands tributary to the area to be benefitted by the Pacific Southwest Water Plan. The survey area included nearly 42 million acres of National Forest lands tributary to the Colorado River, the Central Valley of California, and the coastal area of southern California. Only the Colorado River portion of the survey was reviewed for this paper.

The survey and analysis were conducted in 1967 and 1968 by teams of USDA Forest Service specialists representing the disciplines of hydrology, soils, and ecology. Hydrologic subprovinces averaging about 700,000 acres in size were delineated based on similarities in physiographic and hydrometeorologic characteristics. However, due to the large variation in climate and in geology, soils, vegetation, and landform within each subprovince, the actual analysis was made on much smaller areas known as hydrologic areas, which averaged about 11,000 acres in size.

The potentials for increasing water yield were expressed in quantities of additional water which could be made available on National Forest System lands on the unit area treated. They did not reflect the potentials that could be developed on intermingled land of other ownership, or the natural depletions that might occur due to consumptive uses of water or deep seepage between

[25] Pacific Southwest Hydrologic Analysis Phase 1. Unpublished reports were prepared by USDA Forest Service Rocky Mountain Region, Lakewood, Colo.; Southwestern Region, Albuquerque, N. M.; and Intermountain Region, Ogden, Utah.

the point of treatment and any specific point downstream.

The actual computation of water yield potentials was performed by a computerized water balance program using mathematical functions descriptive of the hydrologic processes. Separate computations were made for years of high, average, and low precipitation. Only results for average precipitation are presented in this paper. For reasons not clarified, water yield increases were not always greater for average than for low precipitation years.

The analysis was limited to potential increases that could be achieved by management of forest and shrub vegetation. It did not include the additional potentials that may be attainable by snowpack management in the alpine zone and high elevation grasslands. Only major multiple use constraints were applied, such as wilderness area management and established commercial timber cutting cycle and rotation criteria. Adjustments were not made for multiple use considerations such as protection and enhancement of wildlife habitat and esthetic values. These and other multiple use considerations would be given emphasis during preparation of management prescriptions for specific units of land, and thus a negative adjustment on water yield potentials could be anticipated.

Potentials for established wilderness and primitive areas were determined to assess the values foregone as a result of legislative and administrative constraints. Although these potentials would not be achievable under present mandate, the information gained would be of value in consideration of future wilderness proposals. Only potentials from outside of wilderness and primitive areas are presented in this summary.

Two basic treatments were evaluated for increasing water yield: (1) type conversion on selected noncommercial vegetation areas and (2) sustained yield harvest of timber in commercial timber stands. In addition, in the Upper Basin, treatable areas were separated into snow zones and nonsnow zones for water yield evaluation. If accumulated water content in the snowpack reached an arbitrary 15 inches, the unit was considered to be in the snow zone. All other units were evaluated as nonsnow zone.

The following assumptions guided the Pacific Southwest Hydrologic Analysis evaluation of potentials for increasing water yield.

1. General criteria for nontreatable area included: areas of low potential for vegetation growth due to soil or climatic factors, very shallow and/or highly erodible soils, steep and unworkable slopes, and miscellaneous land types (rock outcrops, rockland, etc.).

2. Type conversion to grass was considered in all areas other than commercial timber forest, and required maintenance work would be done at regular intervals on converted areas. Criteria for selection of treatable areas for type conversion varied, but generally these criteria had to be met:

   (a) Slopes less than 30% (30% to 60% if area had high suitability for grass).

   (b) Low or moderate erodibility and soils deeper than 20 inches.

   (c) High or medium productivity for grass.

   (d) Overstory density greater than 30% (60% for pinyon-juniper).

3. The commercial timber forest would be harvested by clearcutting according to cutting cycles and rotation periods established in timber management plans, but the sequence and pattern of harvest would be modified to fully utilize the opportunities for water yield augmentation. Again, these criteria generally applied:

   (a) Slope less than 60%.

   (b) Overstory canopy density greater than 30%.

   (c) Not a rockland unit.

4. Water yield increases tend to decline as trees regrow after timber harvest. Adjustments were applied to water yield increases to account for the expected decline through the effective periods. The rotation ages and effective water increase periods used in the general water yield evaluation for most areas were:

| | Rotation age in years | Effective water increase period in years |
|---|---|---|
| Spruce fir | 100 | 20 |
| Lodgepole pine | 100 | 20 |
| Ponderosa pine | 120 | 20 |
| Aspen[26/] | 75 | 15 |

In addition, a system of small clear cuts designed specifically for improving water yield was evaluated for the commercial timberland snow zones in Colorado. The effective period also was extended to reflect the slower decline of yield increases that follow these cutting practices.

Of 28.6 million acres of National Forest lands in the Colorado River Basin, only about 11.4 million acres were considered for treatment by the Pacific Southwest Hydrologic Analysis (table 13). Not all suitable acres would actually be treated, although in some areas most would be. Only four classes of vegetation are shown in the summary (table 13), although the analysis was performed on a much more detailed breakdown.

1. Brushland areas are primarily Gambel oak in the Upper Basin and chaparral in the Lower Basin.

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[26/] Except on two national forests in Colorado, aspen was evaluated as type conversion.

Table 13.--Summary of potential increases in water yield (thousands of acre-feet) from treatable acres (in thousands) on National Forest lands in the Colorado River Basin. From Pacific Southwest Hydrologic Analysis.

| Subbasins | Brush-lands | | Riparian | | Commercial forest | | Noncom-mercial forest | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Treat-able acres | Acre-feet | Treat-able acres | Acre-feet | Treat-able acres | Acre-feet | Treat-able acres | Acre-feet | Treat-able acres | Acre-feet |
| Upper Basin | | | | | | | | | | |
| Green River | 72 | 3 | - | - | 1,765 | 55 (148) 1/ | 706 | 98 | 2,543 | 156 (349) 1/ |
| Upper Main Stem | 112 | 14 | - | - | 2,296 | 115 (370) | 539 | 136 | 2,947 | 265 (520) |
| San Juan-Colo. | 149 | 14 | - | - | 1,143 | 39 (74) | 48 | 1 | 1,340 | 54 (89) |
| Basin Total | 333 | 31 | - | - | 5,204 | 209 (692) | 1,293 | 235 | 6,830 | 475 (958) |
| Lower Basin | | | | | | | | | | |
| Lower Main Stem | 259 | 8 | - | - | 418 | 10 | 114 | 1 | 791 | 19 |
| Little Colo. | - | - | - | - | 909 | 24 | 275 | 2 | 1,184 | 26 |
| Gila | 981 | 229 | 69 | 8 | 1,336 | 55 | 256 | 5 | 2,642 | 297 |
| Basin Total | 1,240 | 237 | 69 | 8 | 2,663 | 89 | 645 | 8 | 4,617 | 342 |
| TOTAL COLORADO RIVER BASIN | 1,573 | 268 | 69 | 8 | 7,867 | 298 (781) | 1,983 | 243 | 11,447 | 817 (1,300) |

1/ Figures in parentheses are combined increases (not in addition to the others) when timber harvest practices in the snow zone are scientifically designed for water yield improvement.

2. Riparian vegetation consists of trees and shrubs along relatively small streams draining the highlands. Since only National Forest lands were considered, most downstream phreatophyte concentrations were not considered. Only 69,000 acres of riparian vegetation were delineated; all were in the Gila Subbasin.
3. Commercial forest includes the spruce-fir type, lodgepole pine, mixed conifer, Douglas-fir, ponderosa pine, and aspen. In the snow zone, much larger increases in water yield (figures in parenthesis in table 13) were considered possible by timber harvest practices scientifically designed for water yield improvement.
4. Noncommercial forests consist of marginal timber stands, aspen (where not classified as commercial), pinyon-juniper, and some of the mountain brush in the Upper Basin. Large increases attributed to noncommercial forests in the Upper Basin (table 13) were mostly from type conversion of aspen.

The potential increase in water yield was estimated at 475,000 acre-feet from the Upper Basin and 342,000 acre-feet from the Lower Basin for a total of 817,000 acre-feet. If timber harvest were specifically designed for water yield improvement in commercial forests of the snow zone, an additional 483,000 acre-feet was considered possible, which would raise the Upper Basin contribution to 958,000 acre-feet, and the total of 1,300,000 acre-feet.

Chaparral was considered to have the highest potential for increasing water yield in the Lower Basin. Most of the 268,000 acre-feet was attributed to 981,000 acres of brushlands in the Gila Subbasin, for an average increase in depth over the treatable area of 2.8 inches per year.

### Comprehensive Framework Studies Estimates for Colorado River Basin 1971

The Upper and Lower Colorado Region Comprehensive Framework Studies (PSIAC 1971a, 1971b) stemmed from recommendations of the Senate Select Committee on National Water Resources. The studies were approved by Congress and funds were provided to start the program in 1967. The states of Arizona, California, Nevada, New Mexico, Utah, Colorado, and Wyoming par-

ticipated with various federal agencies in the investigation. The basic objectives were to provide a broad guide to the best use, or combination of uses, of water and related land resources in each region to meet foreseeable short-term and long-term needs.

The reports are voluminous and detailed (18 appendices in addition to the main report for each region), but only those portions dealing with augmentation of water resources are summarized here. The appendices found to be most useful for each region were Water Resources (Appendix V), Land Resources and Use (Appendix VI), Watershed Management (Appendix VIII), and the main Reports.

In developing the Comprehensive Framework Studies, the committee members had available to them the preliminary results of the Pacific Southwest Hydrologic Analysis. However, in addition to National Forest lands, they included lands in other ownerships for projecting potential increases in water yield by management of vegetation.

The Upper Colorado Region Comprehensive Framework Study placed little emphasis on water yield improvement, probably because water supply was considered adequate to meet regional needs for some time in the future. The estimate given for the Upper Region (Appendix VI, p. 129) was 217,000 acre-feet of water increase possible by year 1980, and 434,000 acre-feet by year 2000 and beyond. The treatable acreage required to get these yield increases was estimated at 377,000 acres by 1980, and additional 379,000 acres by 2000, and another 75,000 acres by 2020, for a total of 831,000 acres. Treatment methods considered were type conversion and specifically designed timber harvest practices (Appendix VIII, p. 58). In terms of depth over treated area, these increases average more than 6 inches, a much more optimistic value than estimates by other investigators. Installation costs of the treatments were estimated at about $18 per acre (1965 prices), but costs per acre-foot of increased yield were not given.

Lower Region estimates of water yield increases were based on type conversion of chaparral to grass, harvest of timber, and eradication of phreatophytes along major streams. The average annual increase in water yield in the Lower Region was estimated at 1.1 million acre-feet from 5.1 million suitable acres (Lower Region Main Report, p. 59). The estimate was then qualified by stating that the amounts actually realized would be much less than this potential because of such considerations as esthetics, outdoor recreation, wildlife habitat requirements, and other land management objectives. The estimates are listed by subbasins in table 14.

Eradication of 261,000 acres of phreatophytes along the lower main stem of the Colorado River, the Little Colorado River, and the Gila River was projected to save 624,000 acre-feet of water, more than one-half of the total regional estimate. Within the Gila subbasin 59,000 acres of upstream riparian vegetation were found suitable for treatment. However, probably no more than 10% of this area was actually considered for treatment because the anticipated increase was only 6,000 acre-feet.

An increase of 241,000 acre-feet of water was estimated from type conversion on 1,232,000 acres of chaparral in the Gila Subbasin (essentially the same amounts projected by the Pacific Southwest Hydrologic Analysis, table 13). The

Table 14.--Potential increases in water yield (thousands of acre-feet) from suitable acres (in thousands), considering lands of all ownerships in the Lower Colorado Region. From Lower Colorado Region Comprehensive Framework Study (PSIAC 1971b).

| Subbasins | Chaparral | | Phreatophytes | | Conifer forest | | Pinyon-juniper | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Treatable acres | Acre-feet | Treatable acres | Acre-feet | Treatable acres | Acre-feet | Treatable acres | Acre-feet | Treatable acres | Acre-feet |
| Lower Main Stem | -- | -- | 141 | 404 | 440 | 12 | 26 | 1 | 607 | 417 |
| Little Colorado | -- | -- | 20 | 20 | 1,431 | 78 | 227 | 2 | 1,678 | 100 |
| Gila | 1,232 | 241 | 159 [1] | 206 [1] | 1,301 | 133 | 84 | 5 | 2,776 | 585 |
| Region Total | 1,232 | 241 | 320 | 630 | 3,172 | 233 | 337 | 8 | 5,061[2] | 1,102[2] |

[1] These figures include 59,000 acres of upstream riparian vegetation for an increase of 6,000 acre-feet.

[2] Without phreatophytes, these Region totals are 4,800,000 treatable acres and 478,000 acre-feet of increase water yield.

next largest source of extra water was the commercial conifer forest type where 223,000 acre-feet was projected from more than 3 million suitable acres (both amounts much larger than projected by the Pacific Southwest Hydrologic Analysis, table 13). However, it was assumed that one-third (about 1.1 million acres) of the suitable acreage could provide the 223,000 acre-feet of increase. This smaller acreage would require that production be sustained at about 2.5 inches of yield increase. The contribution from pinyon-juniper vegetation was considered minor. Without phreatophytes, the total potential increase would total only 478,000 acre-feet from 4,800,000 suitable acres. However, this amount is still 137,000 acre-feet more than the 342,000 acre-feet estimated for National Forest lands only in the Lower Region by the Pacific Southwest Hydrologic Analysis.

Cost estimates of increased water yield per acre-foot (1965 prices) were made for all vegetation types. Cost estimates included treatment plus maintenance costs averaged over the projection period. Costs for treatment in the commercial conifer forests included only additional costs over those incurred from normal timber harvesting. Costs were estimated to be as low as 50 cents and as high as $150 per acre-foot. Costs exceeding $150 per acre-foot were considered excessive, and these areas were not included with otherwise suitable areas for water yield improvement programs. Average costs per acre-foot by vegetation type were: chaparral $18, conifer forests (commercial) $4.50, pinyon-juniper $95, riparian vegetation $20, and phreatophytes $2.50. The overall average for all vegetation types was about $17 per acre-foot. Without phreatophytes or pinyon-juniper, the average for 464,000 acre-feet of increased yield in the chaparral and conifers was $12 per acre-foot.

### Ffolliott and Thorud Estimates for Arizona Only, 1974

In their assessment of the Arizona Watershed Program, Ffolliott and Thorud (1974) reviewed 20 years of research and management experience to update the first serious effort in the mid 1950's (Barr 1956) to evaluate potentials for increasing water yield by vegetation management. The main objective of the Ffolliott-Thorud analysis was to define maximum potentials for increasing water yield from Arizona's watersheds. The authors caution that their estimates have a hypothetical structure based on stated assumptions of water yield response to different levels of vegetation manipulation, and that under operational land management practices many constraints may operate to reduce the potentials given. The only exclusions to possible treatment were areas of low precipitation and areas in ownerships that preclude manipulation of vegetation for water yield purposes, such as National Park lands. Wilderness areas on National Forest lands were included.

Nine vegetation zones were recognized in the analysis, although only three were considered to have significant potential for water yield increases. Potentially treatable acres and estimates of potential increases for mixed conifer, ponderosa pine, and chaparral vegetation were determined for each of 15 drainage areas within Arizona. These 15 areas were combined into three subbasins in this summary (table 15) to make comparisons easier with other estimates of water yield potential in the Lower Colorado Basin.

Up to 12 management options were evaluated on the three vegetation types. The range in potential water yield increase at average conditions was calculated at between 600,000 and 1,200,000 acre-feet per year for Arizona as a whole. These were onsite increases with no allowance for downstream transmission depletions. Also, the assumption was made that all treatments would be made at one time in order to illustrate full potential. The estimates did not include increases that may be achieved by managing phreatophyte vegetation, although it was assumed that the potential would average 2 acre-feet per acre annually for any areas that might be treated.

The greatest potential for increasing streamflow was attributed to management of ponderosa pine forests by clearing two-thirds of the treatable acreage in uniform or irregular strip cuts to give 0.2 acre-foot/acre/year extra water. A thinning operation, removing 75% of the basal area to approximately 30 square feet per acre, would give an intermediate water increase of 0.15 acre-foot/acre/year, and a low option would clear one-third of the treatable acreage, also in strip cuts for an increase of 0.1 acre-foot/acre/year. Treatable acres of ponderosa pine forests included all National Forest, Indian tribal, state, and private lands receiving at least 20 inches of annual precipitation.

Chaparral was considered the next most important potential producer of water by converting 60% of treatable areas to grass for a yield increase of 0.2 acre-foot/acre/year. A low option would convert 40% of the area for an increase of 0.1 acre-foot/acre/year. Treatable acres of chaparral were all National Forest, Indian tribal, state, and private lands receiving at least 16 inches precipitation annually.

The least important producer was the mixed conifer type, although the greatest yield increase per unit area was attributed to this type. It was assumed that a high option of treatment severity would give approximately 0.5 acre-foot/acre/year increase by converting to grass-forb cover two-thirds of the area located immediately adjacent to stream channels. Likewise, a low option would give 0.1 acre-foot/acre/year increase by converting one-third of the area located next to stream channels.

Yield increases would occur mostly in the central highlands and eastern mountain areas. About one-half of the potential was attributed to the Salt and Verde River Basins above Phoenix (Salt-Verde portion of Gila Subbasin). Next was the Little Colorado River (Arizona portion) with about 17%, followed by the upper Gila River (Arizona portion) with about 8% of the total.

Table 15.--Potential water yield increase for (thousands of acre feet) for Arizona (thousands of acres) summarized from Ffolliott and Thorud (1974). Data are arranged by Subbasins within the Lower Colorado Basin, but includes only those portions within Arizona.

| Vegetation Zone | Delineated Area | Treatable Area | Potential Increases Low | Potential Increases High |
|---|---|---|---|---|
| Lower Main Stem Subbasin [1/] | | | | |
| Ponderosa pine | 1,018 | 321 | 32 | 64 |
| Chaparral | 825 | 434 | 43 | 87 |
| | | | 75 | 151 |
| Little Colorado Subbasin | | | | |
| Mixed Conifer | 34 | 31 | 3 | 15 |
| Ponderosa pine | 1,298 | 987 | 99 | 198 |
| | | | 102 | 213 |
| Gila Subbasin | | | | |
| Mixed Conifer | 54 | 52 | 5 | 26 |
| Ponderosa pine | 2,510 | 2,122 | 212 | 424 |
| Chaparral | 2,243 | 2,079 | 208 | 416 |
| | | | 425 | 866 |
| Total Within Arizona | | | | |
| Mixed Conifer | 88 | 83 | 8 | 41 |
| Ponderosa pine | 4,826 | 3,430 | 343 | 686 |
| Chaparral | 3,068 | 2,513 | 251 | 503 |
| TOTAL | | | 602 | 1,230 |

[1/] Included in this subbasin is that portion of northeastern Arizona draining to the San Juan River and Main Stem Colorado above Lee Ferry, encompassing 195,000 acres of ponderosa pine with a potential for 5 to 9 thousand acre-feet of water increase. This area actually is part of the San Juan-Colorado subbasin within the Upper Colorado Basin, but is included here because it is within Arizona.